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14. ABSTRACT
Modern optical components such as aspheres are difficult to inspect. Interferometry, the usual solution, lacks the required dynamic range. Too many fringes are produced. Adapting interferometry for null measurements currently necessitates special optical components for each inspected component. In this effort, a programmable Spatial Light Modulator (SLM) was incorporated into an optical inspection instrument to boost the dynamic range and enable null testing on almost any component using off the shelf optics. The instrument was used to measure the surface accuracy of a 6 inch tall cone with a top diameter of 8.4 inches and a bottom diameter of 8.2 inches. Measurement simulations were compared with test data and the system errors were investigated. A procedure was also developed and tested to subtract system aberrations. A dynamic range of 150 wavelengths was demonstrated.

15. SUBJECT TERMS
Aspheres, Interferometry, Spatial Light Modulator, Surface Accuracy, Optics, Mirror, Zernike, Freeform Optics, Null Testing, Hartman, Wavefront

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Enhanced Interferometry with a Programmable Spatial Light Modulator

Presented at

Mirror Technology SBIR/STTR Workshop

June 7th to 9th, 2010

Millennium Hotel, Boulder CO

by

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(POC's: Geraldine Wright and David Content)

This presentation is approved for General Public release

Presentation Summary

- Summarize the problem & innovation
- Describe the hardware and software
  - Digital Interferometry with preconditioned wavefronts
  - Hybrid Hartmann/Digital Interferometry
- Typical measurements
- Potential Applications
- Future Work

The Problem Being Addressed

Modern optical components such as aspheres are difficult to inspect. Interferometry, the usual solution, lacks the required dynamic range. Too many fringes are produced. Adapting interferometry for null measurements currently necessitates special optical components for each inspected component.

Innovation/Solution

- Incorporate a programmable SLM into an optical inspection instrument enabling:
  - Combined interferometry and Hartmann Sensing
  - Virtually unlimited dynamic range
  - Extended dynamic range of interferometry by preconditioning waves
  - Null testing on almost any component using off the shelf optics.
- Incorporate Instantaneous Digital Interferometry Technology

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Challenges Faced and Solved

- Incorporating the SLM into a PhaseCam
- Integrating Hartmann and Digital Interferometry
- Calibrating the SLM
  - Phase-only mode by controlling polarization
  - Corrected gamma curve, i.e. linear phase shift versus grayscale value
- Impressing the required phase function on the SLM
- Identifying and minimizing errors and noise

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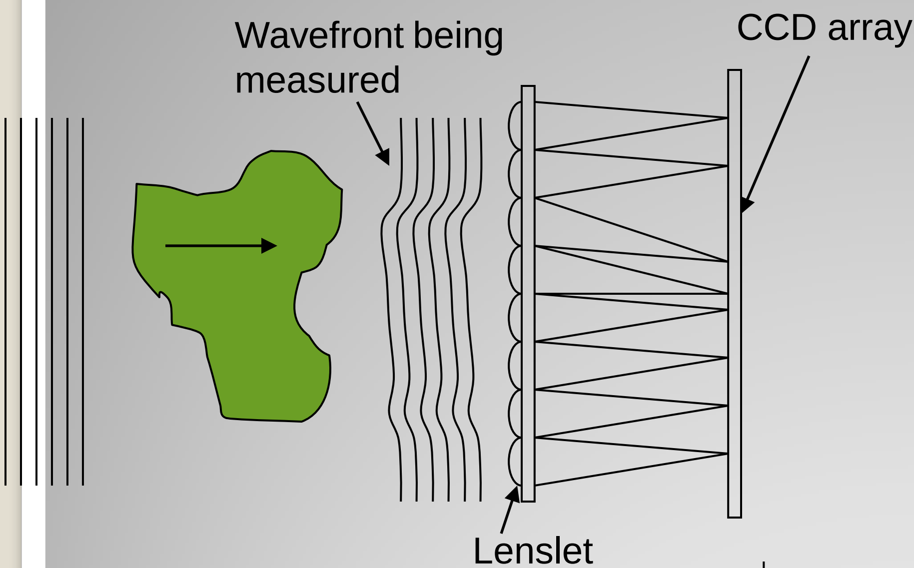
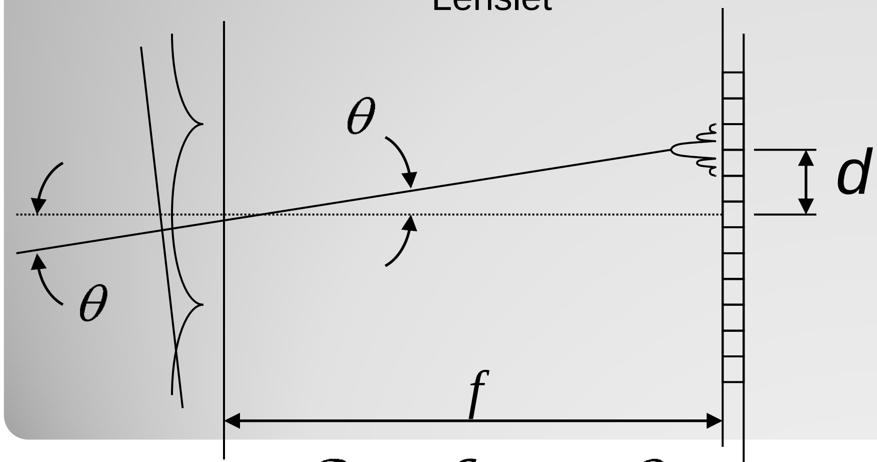
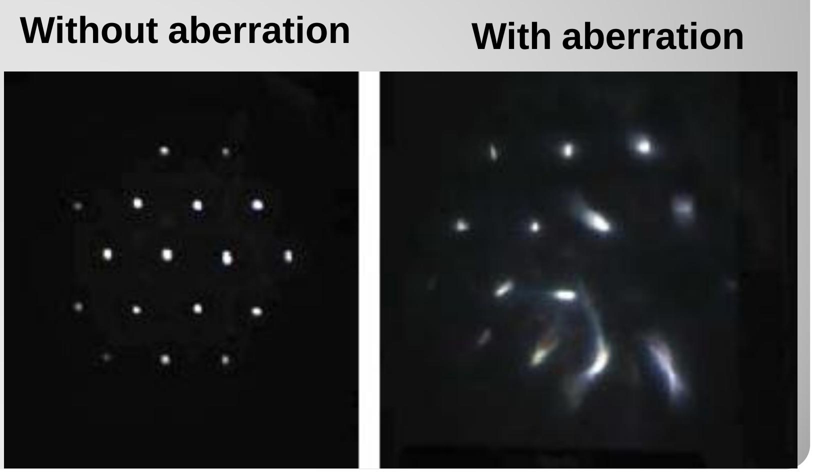
Conventional Shack-Hartmann Characteristics





$$\delta = f \tan\theta$$

- Lenslet diameters, d, define spatial resolution over the wavefront being measured.
- δ (sensitivity) proportional to f, which should be less than d to prevent confusion



'Measuring aberration of the eye with wavefront technology '
Giuseppe Colicchi, et al
Zur Veröffentlichung eingereicht bei "Physics Education", 2006

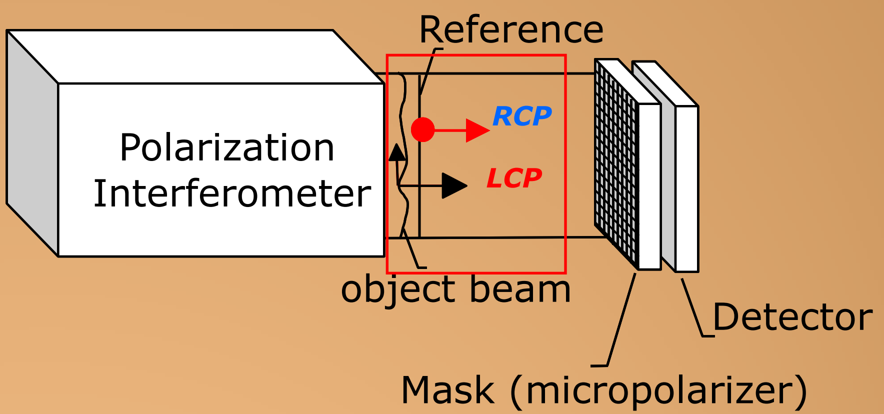
Key Components: SLM, Pixelcam*

SLM for a compensator

- Programmable holographic optical element
- Produce wavefronts of any shape and can simulate freeform optical surfaces
- Holoeye SLM
  - SLM can produce a phase up to 2π at 632.8nm
  - Assign 0 to 255 grayscale values to 0 to 2π (or 1λ)
  - Can generate higher phases by wrapping phase
  - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
  - 19.5 x 14.6mm size (1024 x768 pixels)

Pixelated Phasecam for a detector

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration



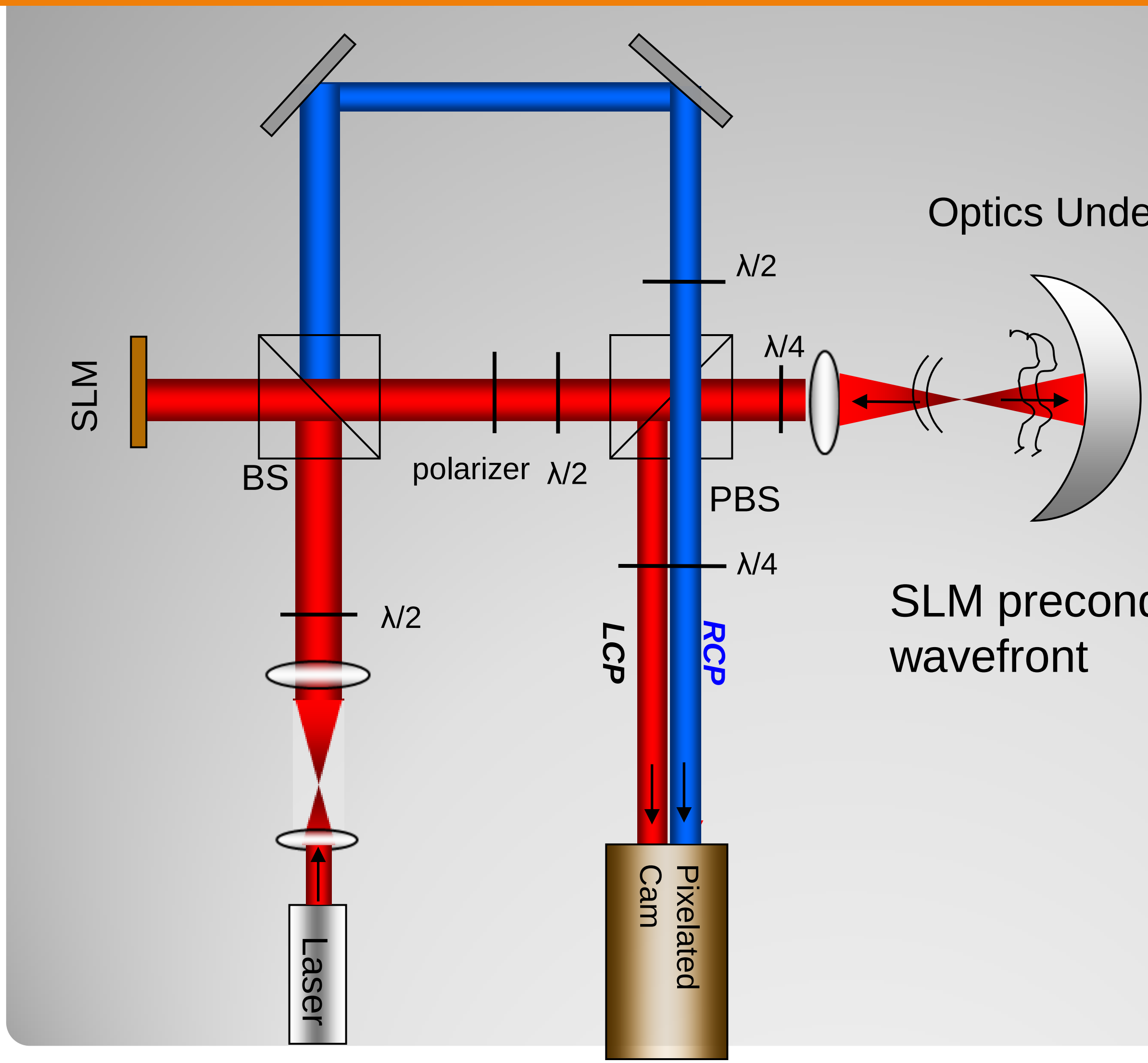
0	90
270	180

Phase information of the object, *ΔΦ(x,y)* can be obtained from the 4 intensities on each unit cell.

$$I(x,y)=\frac{1}{2}\left(I_r+I_s+2\sqrt{I_r I_s}\cos\left(\Delta\phi(x,y)+2\alpha_p\right)\right)$$

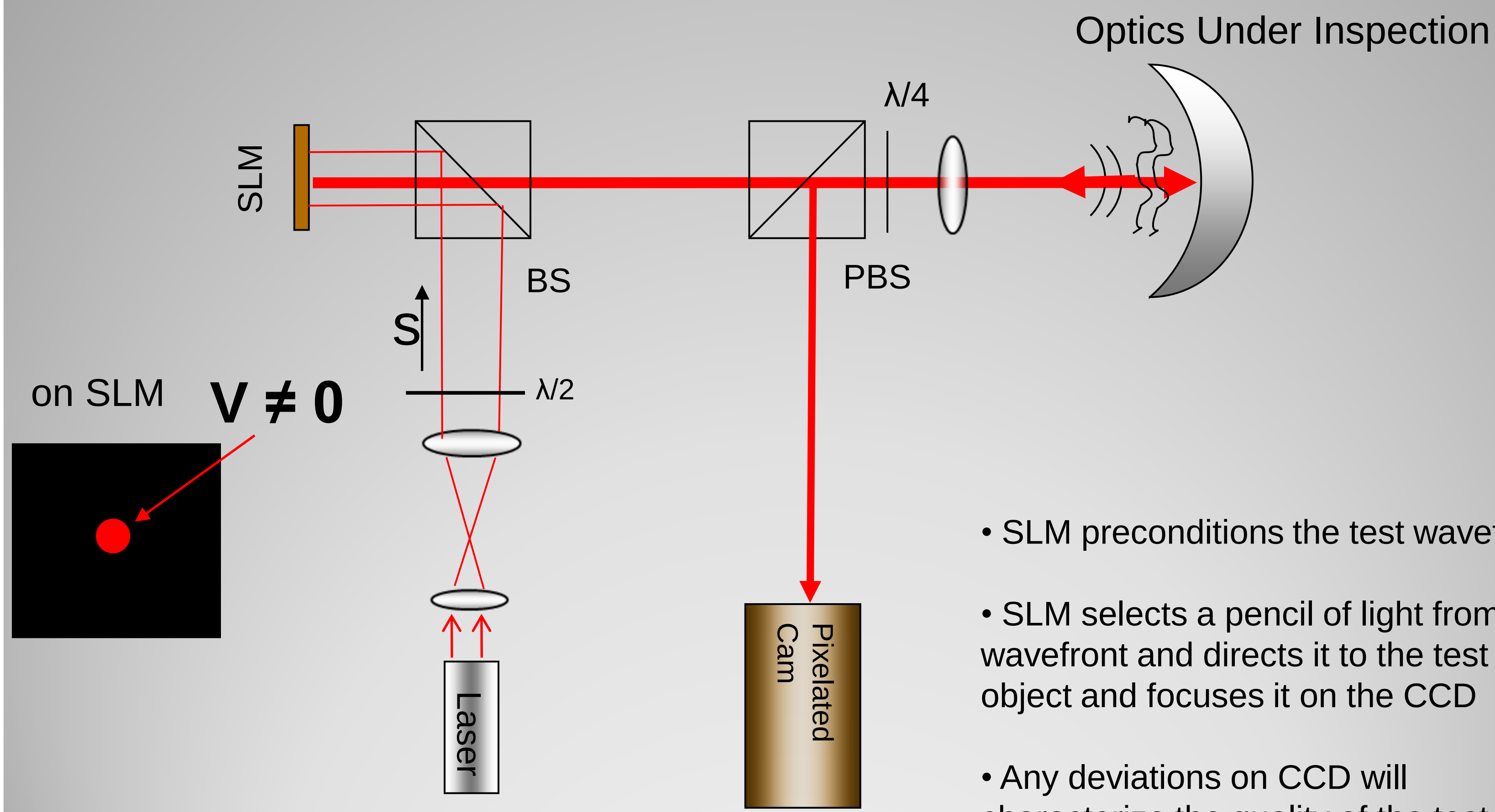
Produced and Trademark by 4D Technologies, Inc, Tucson, AZ* ***http://www.4dtechnology.com*

Hybrid Hartmann & Digital Interferometer



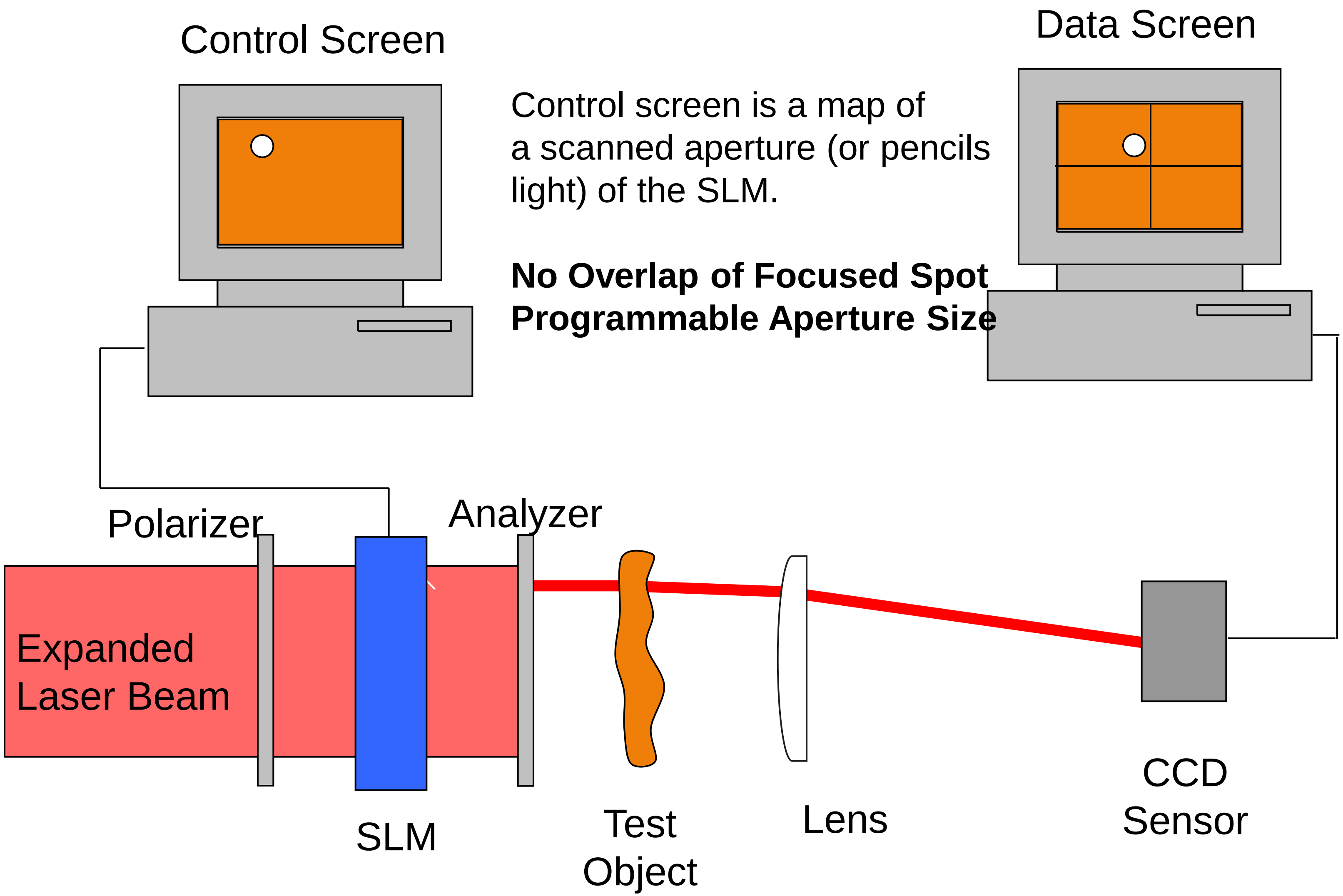
SLM preconditions the test wavefront

Using a SLM as a Scanning Shack-Hartmann Component



- SLM preconditions the test wavefront
- SLM selects a pencil of light from the wavefront and directs it to the test object and focuses it on the CCD
- Any deviations on CCD will characterize the quality of the test object.

Scanning Shack-Hartmann System



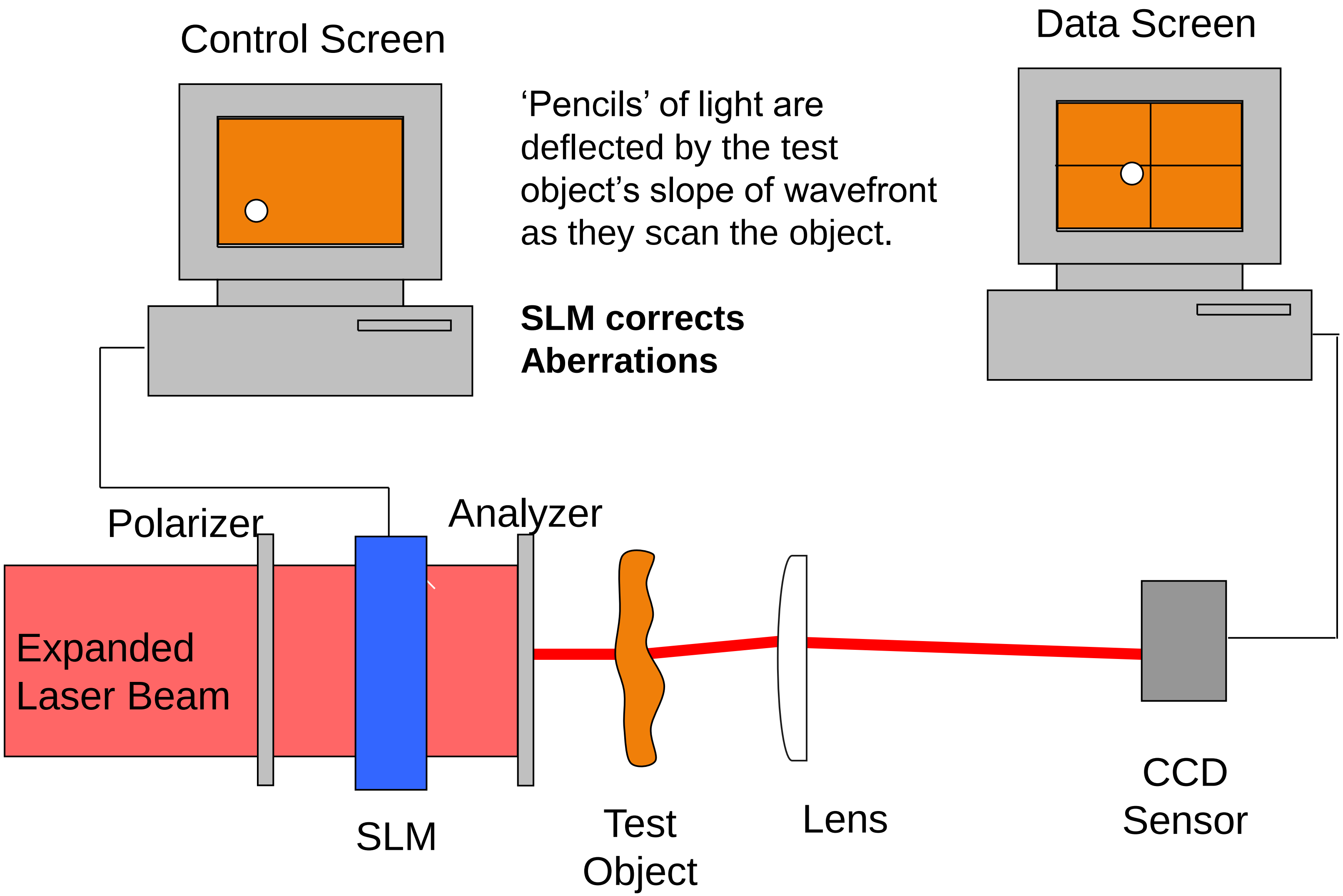
Control screen is a map of a scanned aperture (or pencils light) of the SLM.

No Overlap of Focused Spot
Programmable Aperture Size

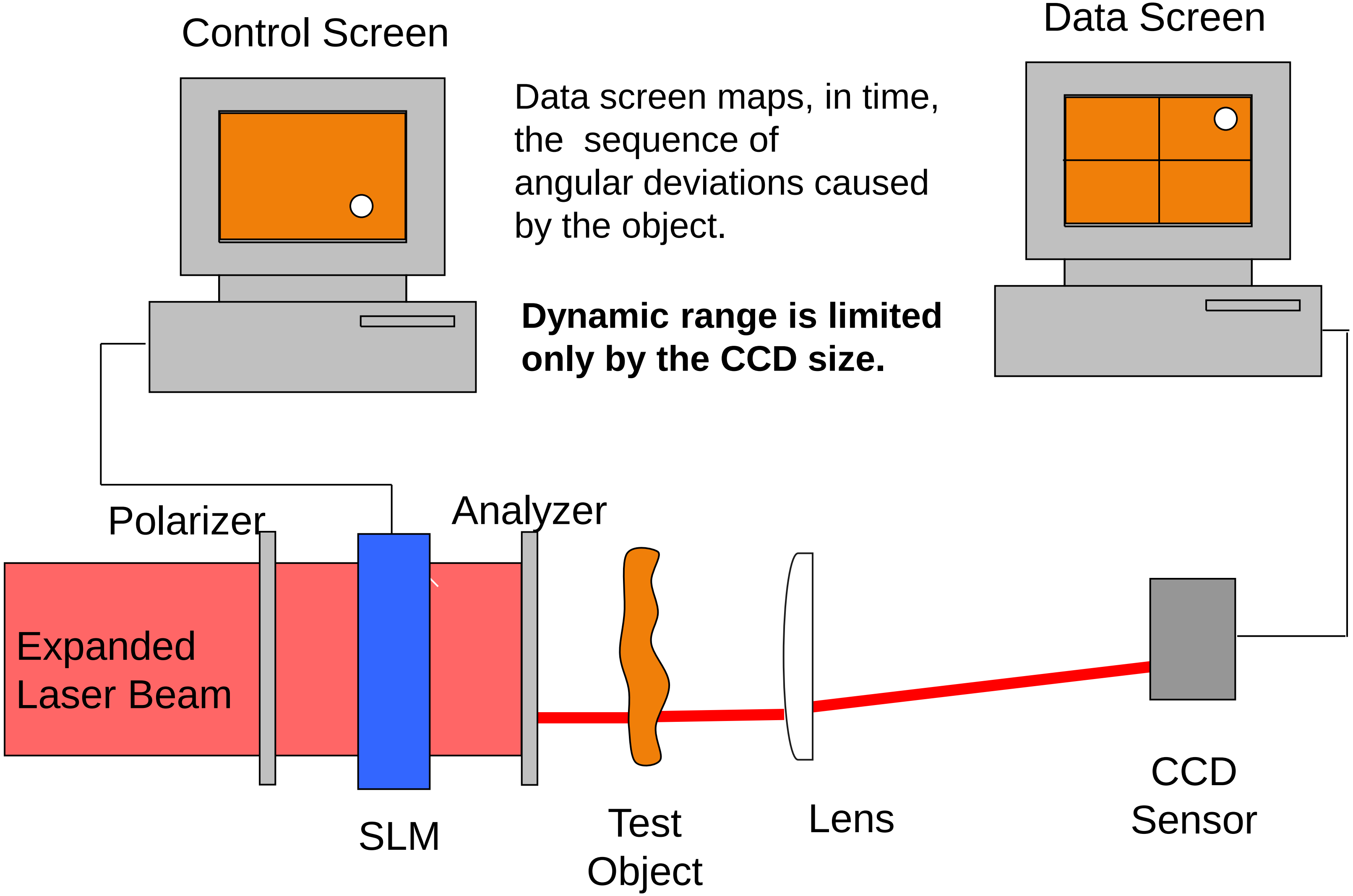
Scanning Shack-Hartmann System

‘Pencils’ of light are deflected by the test object’s slope of wavefront as they scan the object.

SLM corrects Aberrations



Scanning Shack-Hartmann System



Data screen maps, in time, the sequence of angular deviations caused by the object.

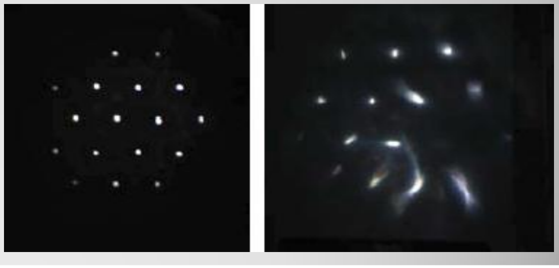
Dynamic range is limited only by the CCD size.

Constraints in conventional Hartmann Testing that can be obviated with this concept

- Sensitivity requires a longer focal length which can cause focused image overlap of adjacent light pencils.
  > SLM enables scanning in time, NO OVERLAP

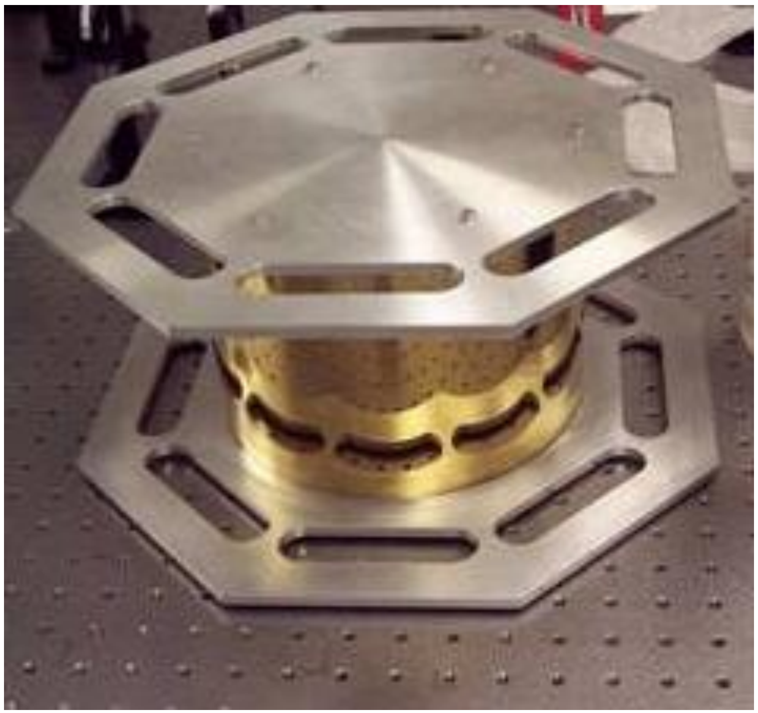
- If the wave is aberrated, the focused spot will not be round, so its centroid is more difficult to locate, further reducing accuracy
  > SLM enables preconditioning/aberration correction

- Spatial resolution is limited to the diameter of the lenses in the array.
  > Limited to fractional pixel size of SLM

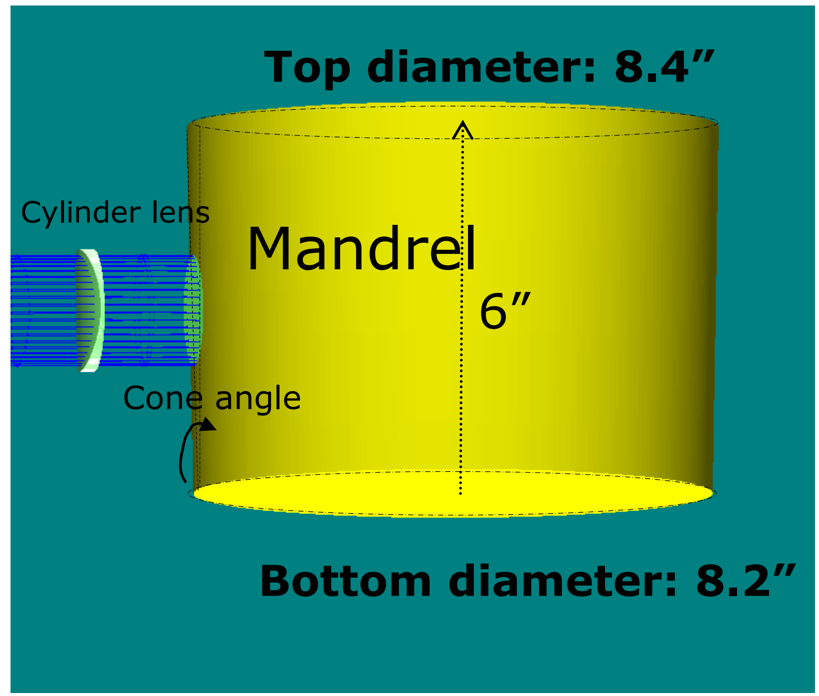


Mandrel Used for Demonstration

Photo of the Mandrel



Geometry of the Mandrel



- Mandrel provided by NASA GSFC, 6-inches tall, top and bottom diameters are different, cone shape.

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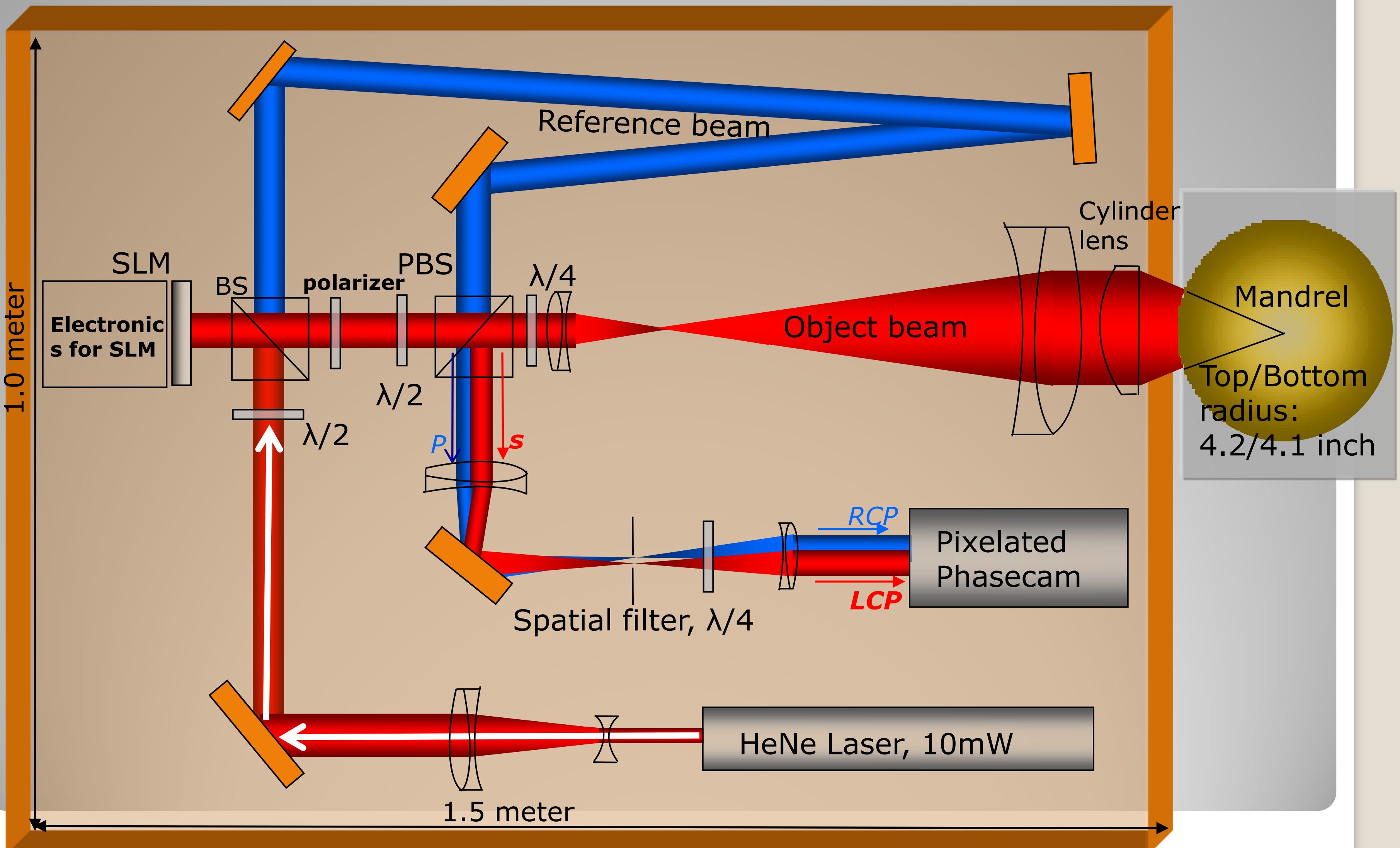
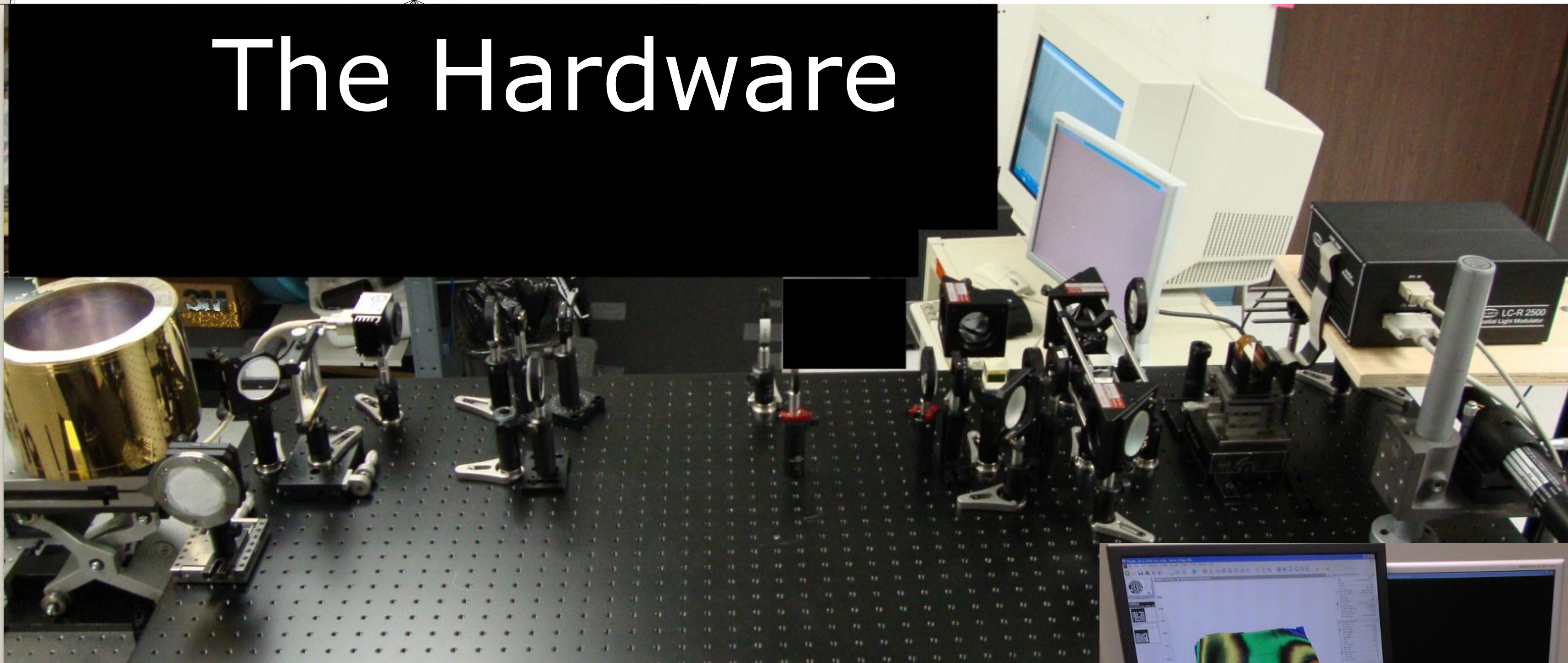
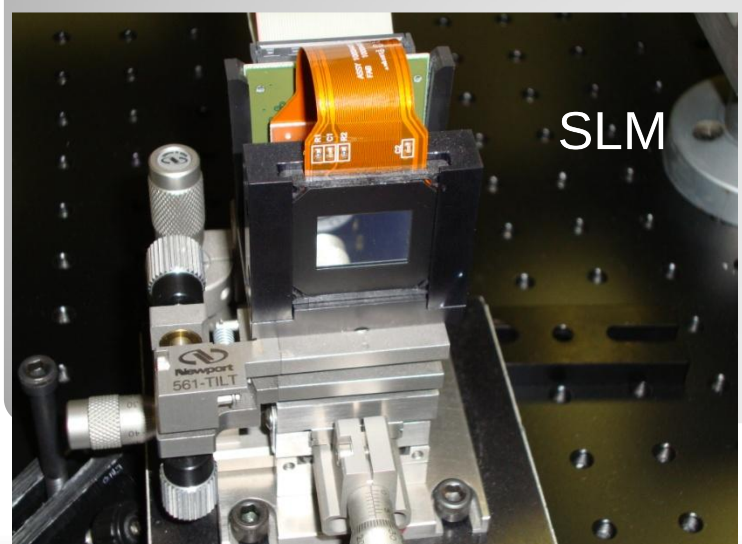
System Design (Top view)



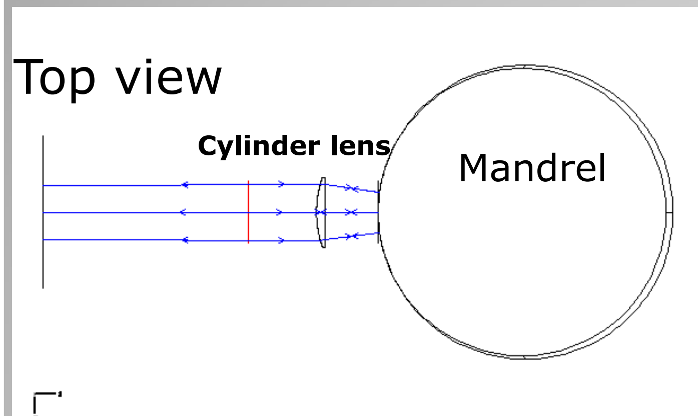
The Hardware

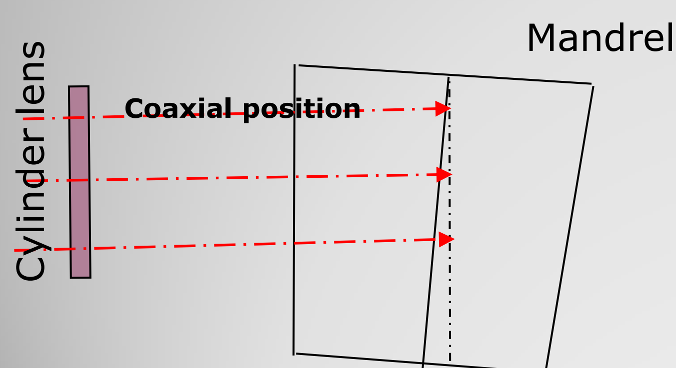




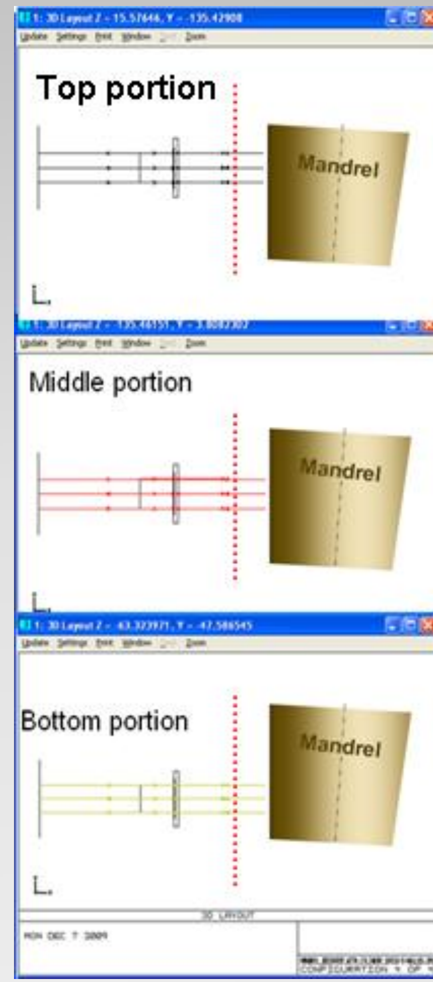
Simulation Results

Beam size at cylinder lens: ~1.8inch
150mm fl cylinder lens

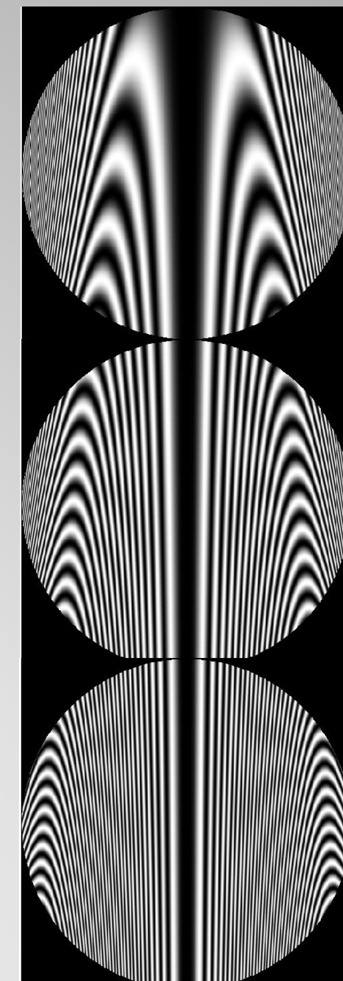




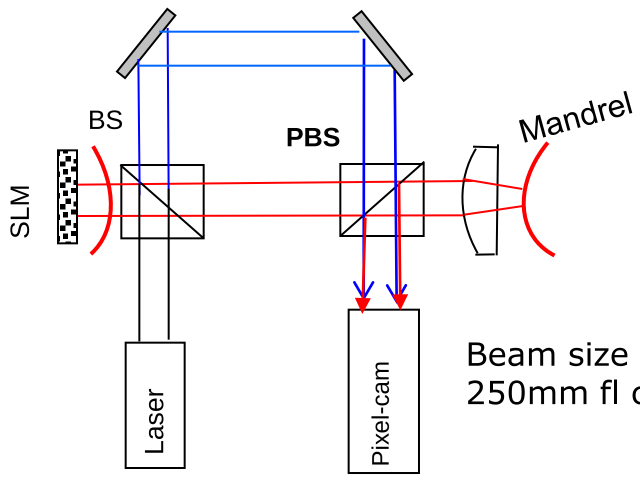
Side View



Interferogram

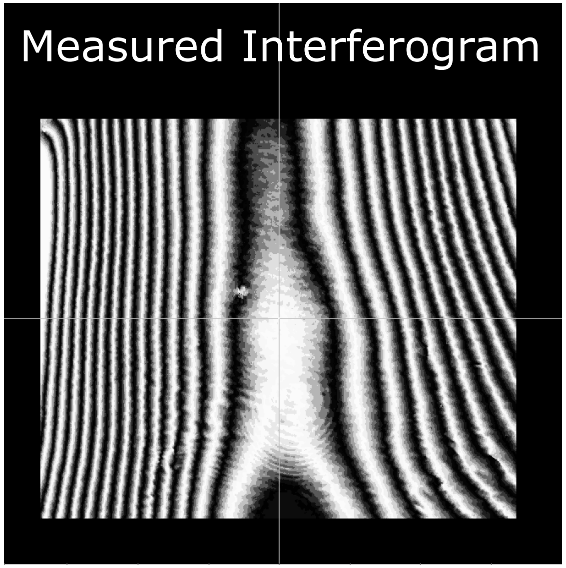


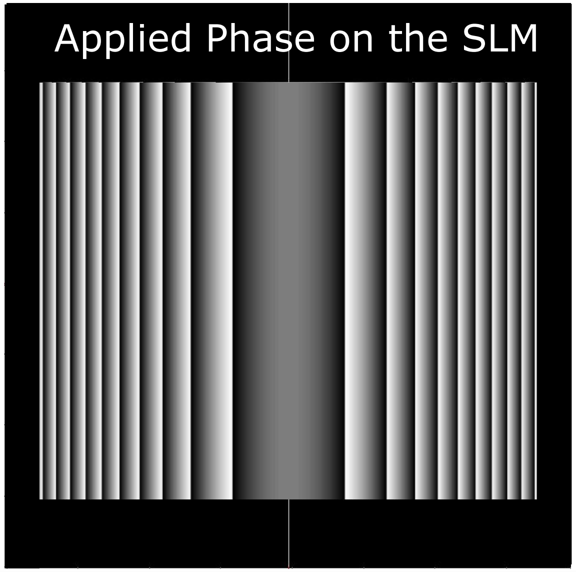
Reducing the number of Fringes from a mandrel

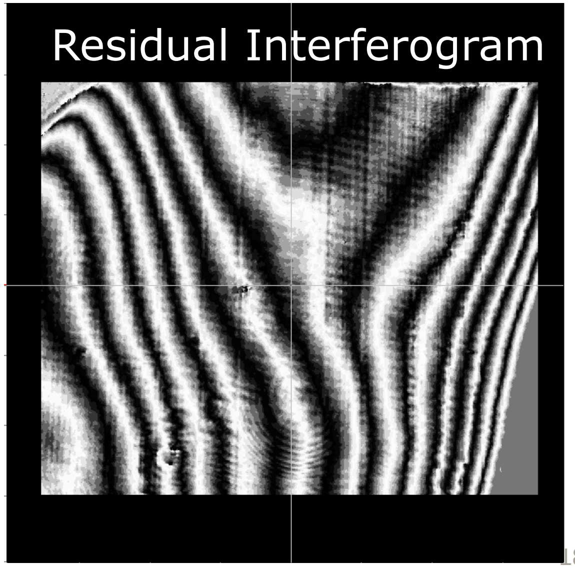


Beam size at cylinder lens: ~1.5inch.
250mm fl cylinder lens used

(Various waveplates and telescopes not shown)

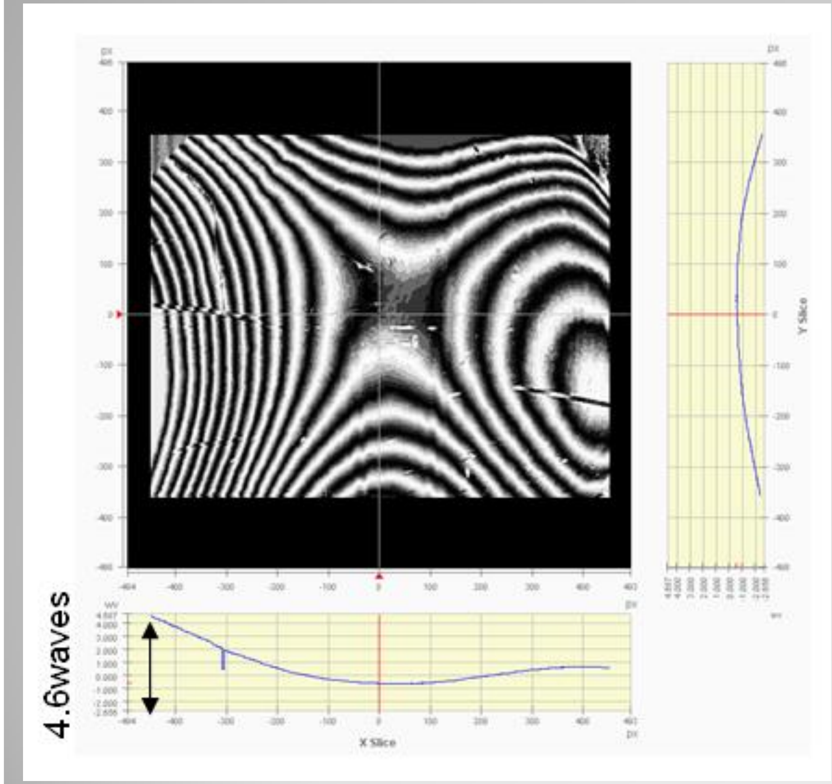




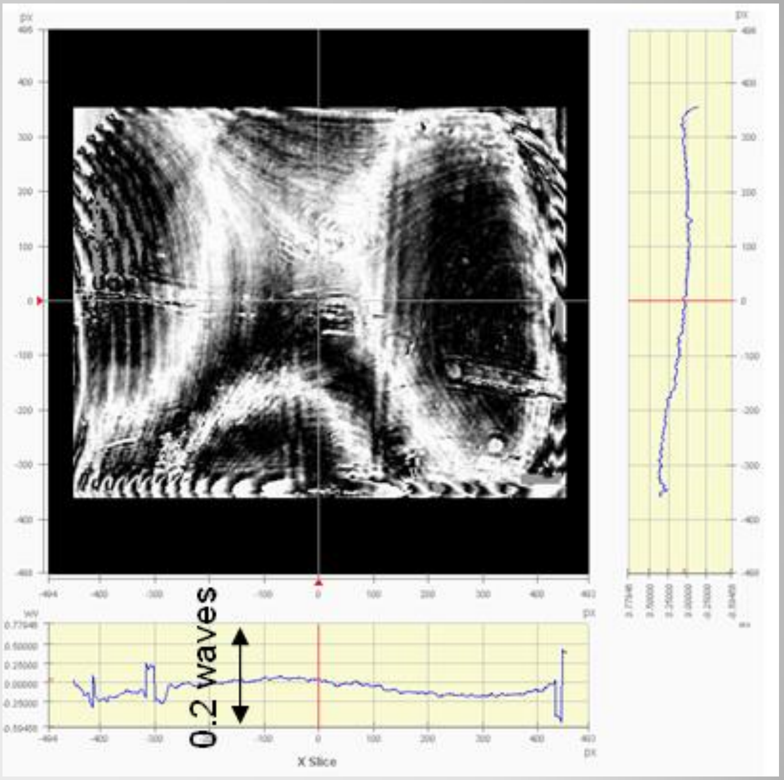


Compensation of one of Mandrel’s wavefronts for a one inch beam

Before Compensation

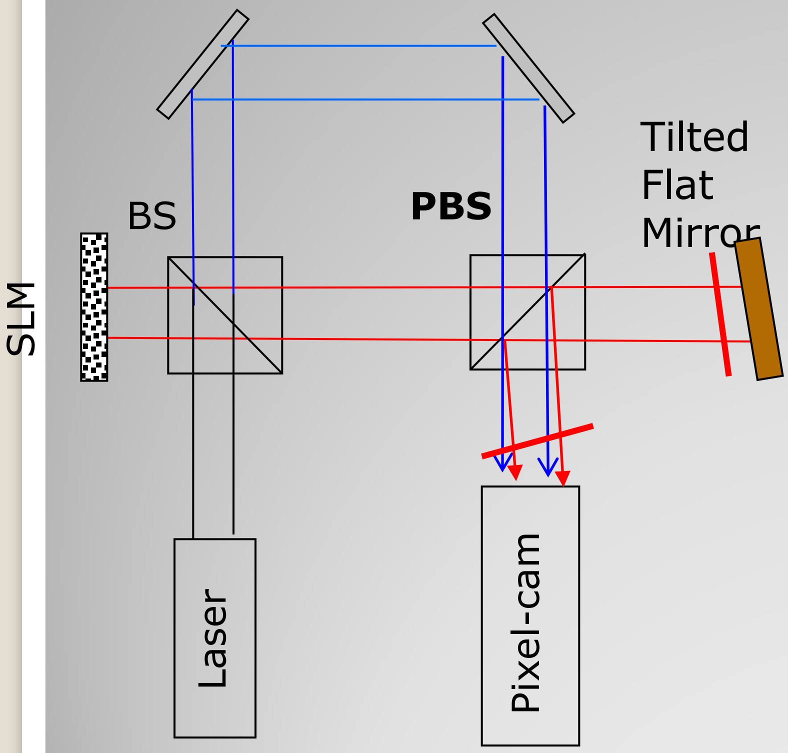


After Compensation



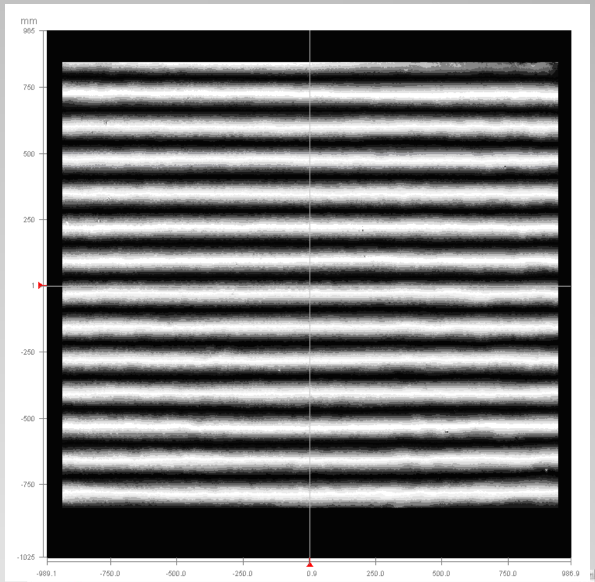
Resolution & Signal to Noise

-Tilt by the flat mirror, ~7 waves



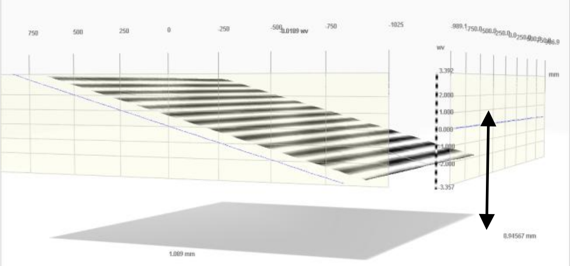
(Various waveplates and telescopes not shown)

Tilt introduced by flat mirror



Interferogram

~ 14 fringes

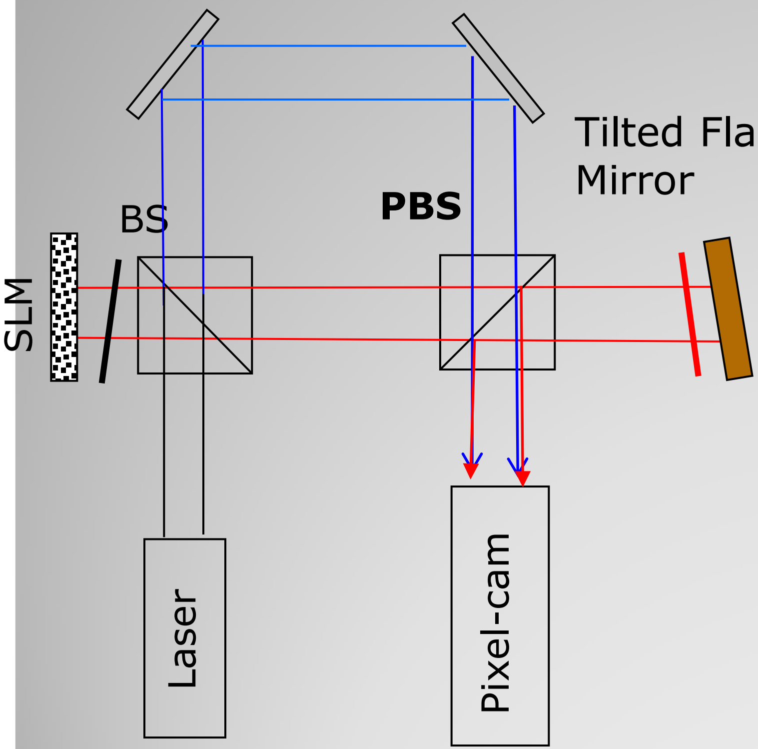


3D view

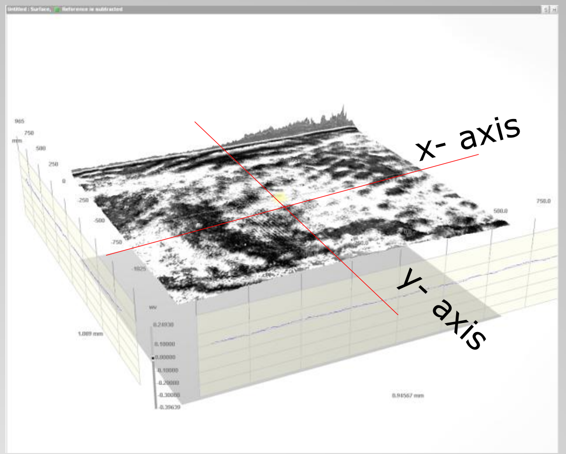
PV. ± 3.4 λ

Resolution and Signal to Noise (Cont.)

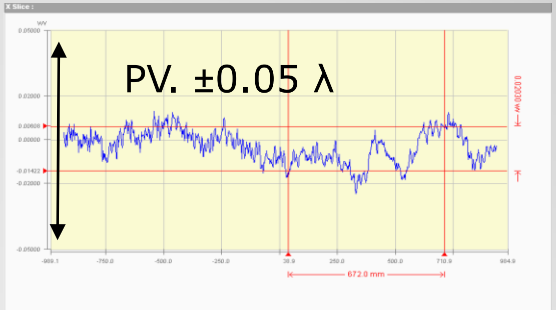
- Residual wavefronts, less than 0.05 λ



(Various waveplates and telescopes not shown)



Interferogram (3D view)

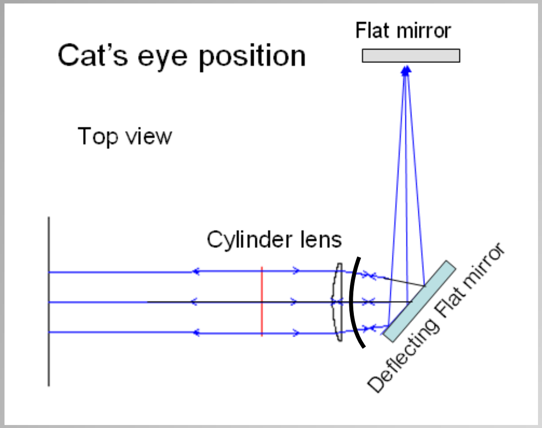


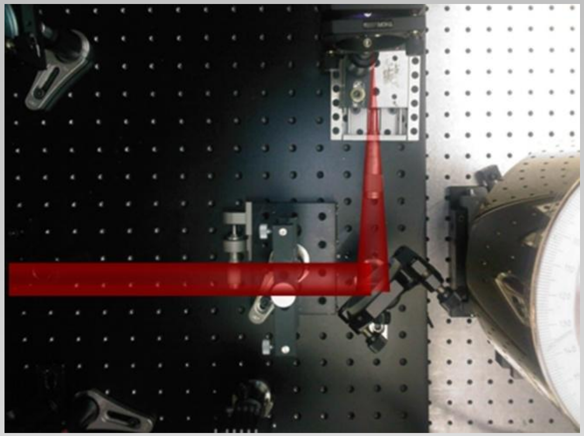
x-profile

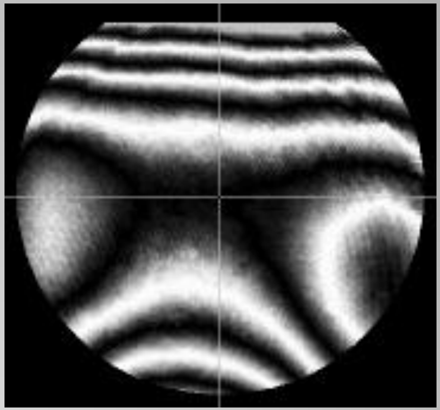
y-profile

SLM can compensate tilted wavefronts with an accuracy of 1/20th wave, or better

Determining System Aberrations with a Cat's Eye

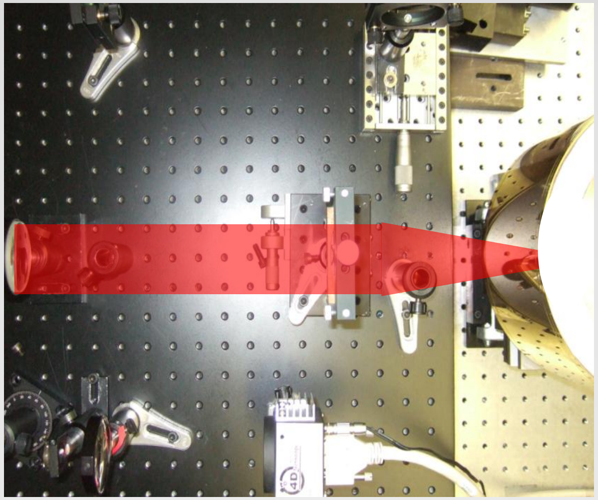


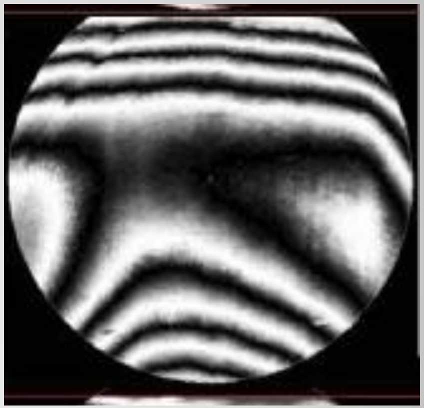




Due to SLM, cylinder lens, optical alignments, etc

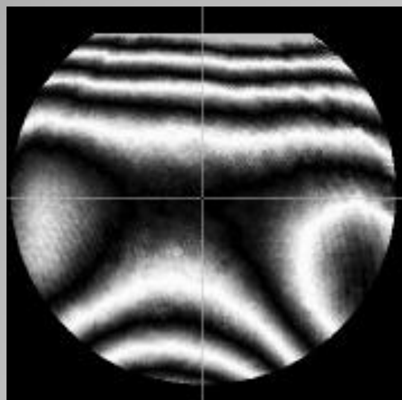
Coaxial position



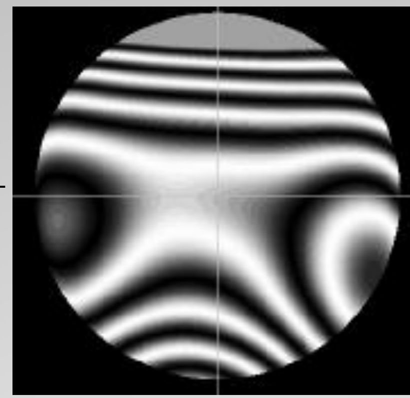


Cat's eye wavefronts by ZEMAX based on Experimental results

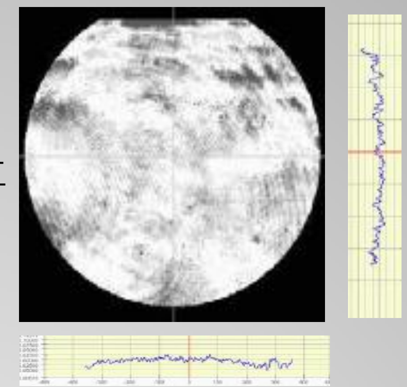
Experimental measurement



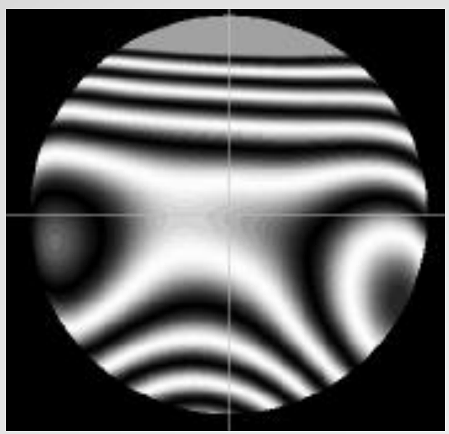
Simulated Fringes



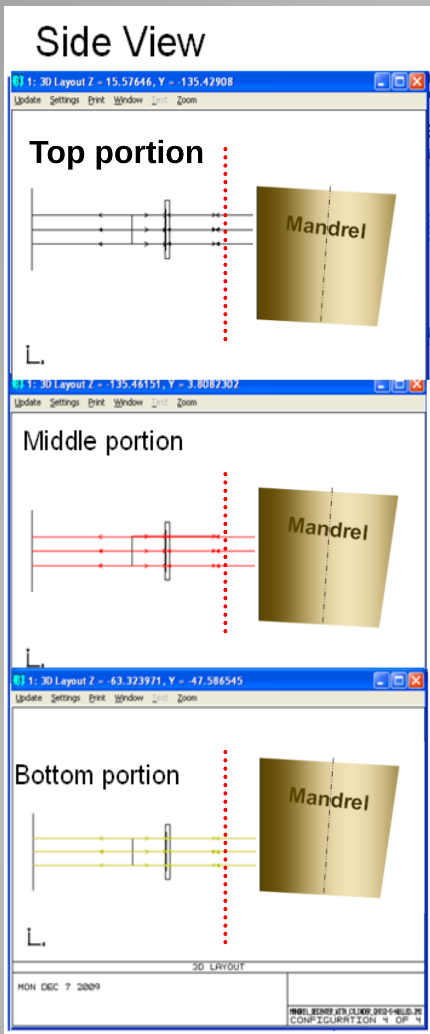
Leftover < 0.1λ



Fitted Zernike Polynomials upto 36 terms, found and put into Zemax

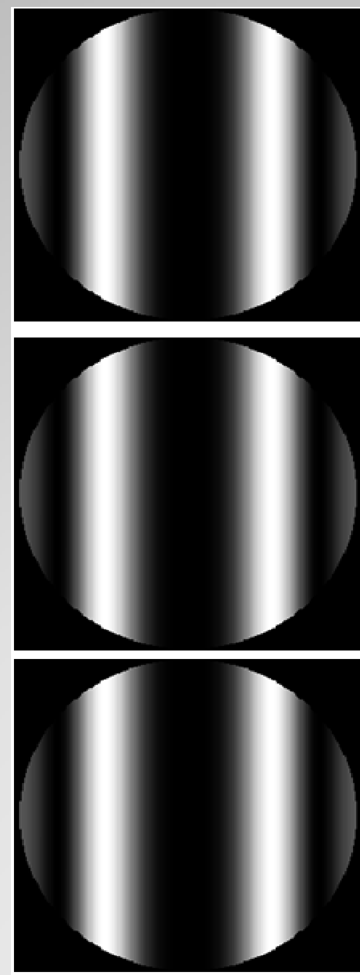


Simulated Cats' eye wavefronts by ZEMAX

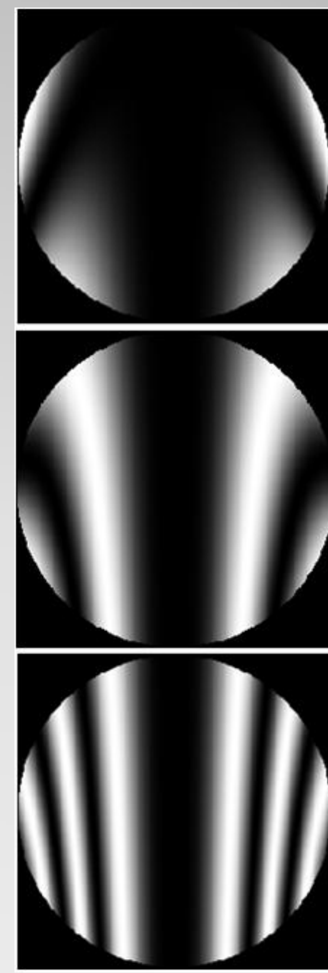


Beam : ~27mm

Simulated, No System Aberrations

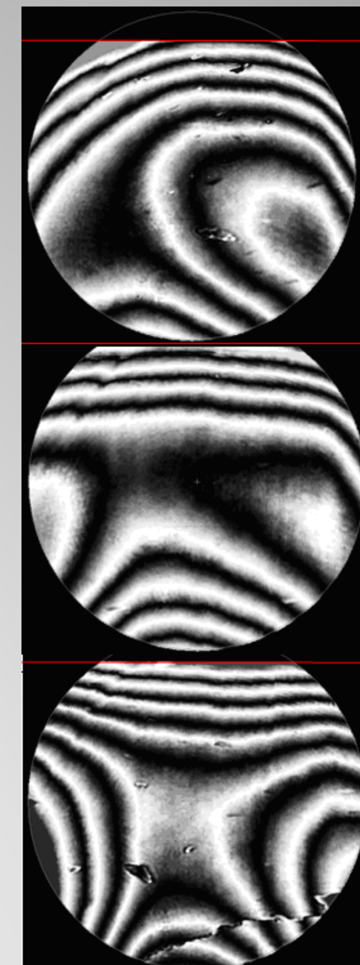


Wavefronts at cat's eye position at each height



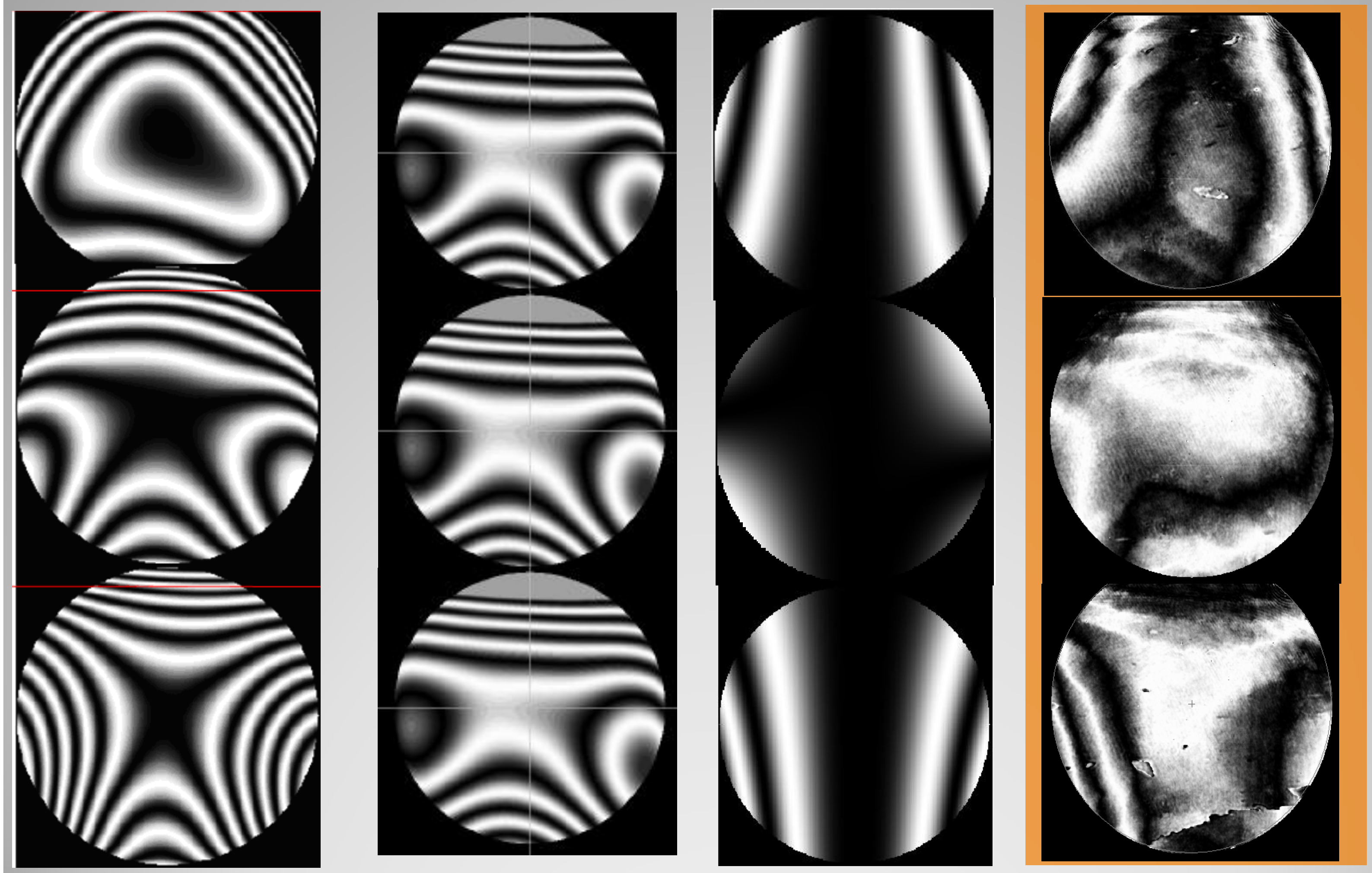
Wavefronts at coaxial position at each height

Measured



Wavefronts at coaxial position at each height

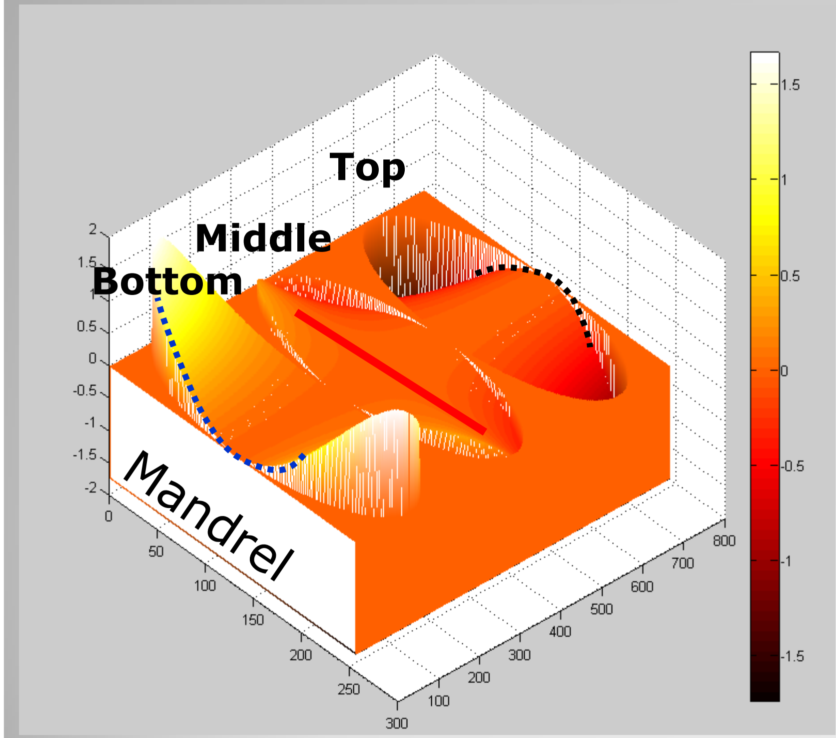
Net fringe due to a Mandrel



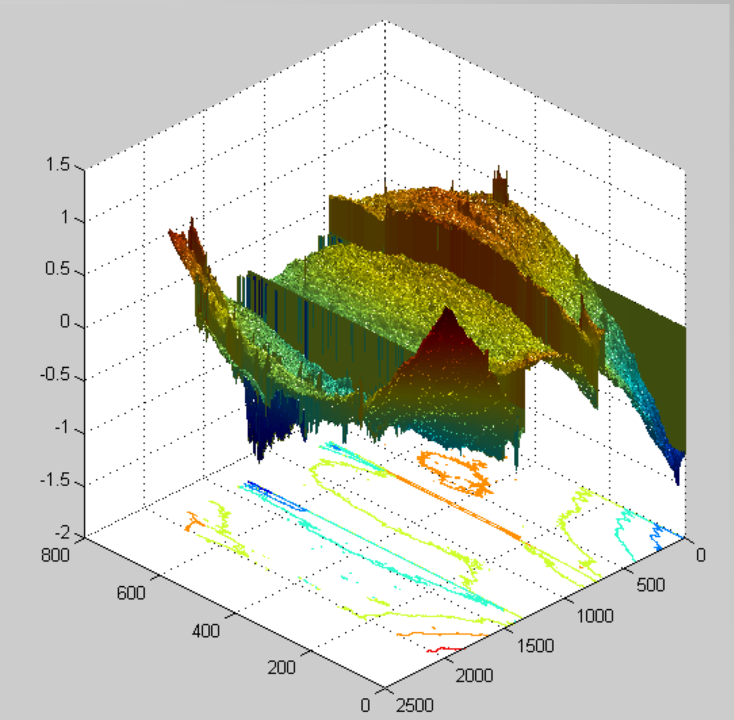
Coaxial position **-** **Cat's eye position** **=** **Simulated Net Fringes** **Experimental Net Fringes**

Wavefronts from the Mandrel, II

Simulated Wavefronts of the Mandrel



Experimental Wavefronts



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Unique Features & Applications

- Very wide dynamic range
- Applicable to aspheres and non axi-symmetric optics, i.e. freeform optics
- Enables null point testing
- Enables removing system aberrations

Summary and Conclusions

- Demonstrated wide dynamic range digital interferometry/Hartmann for advanced optical components using an SLM to:
  - provide wavefront preconditioning.
  - Hartmann & Interferometry in the same instrument
  - Scanning Hartmann
  - extended dynamic range.
  - Null point testing.
- Hartmann provides information needed to program SLM for wavefront preconditioning
- SLM Calibration procedure to produce Gamma curve.
- Procedure to subtract system abberations.
- Accuracy of $\lambda/20$ with SLM in system.
- Concept extends dynamic range by more than 150λ

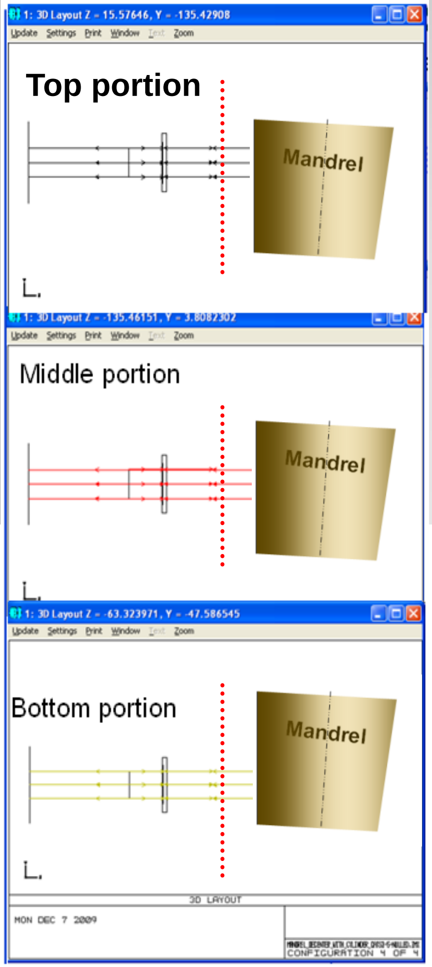
Future Work

- Software Development
  - Transforming Hartmann data into wavefront Preconditioning data.
  - Automating Calibration
  - Interferogram stitching
  - System automation
- Hardware improvements
  - Calibration to push system accuracy
  - Incorporating improved SLM's
  - System packaging

Back up Slides

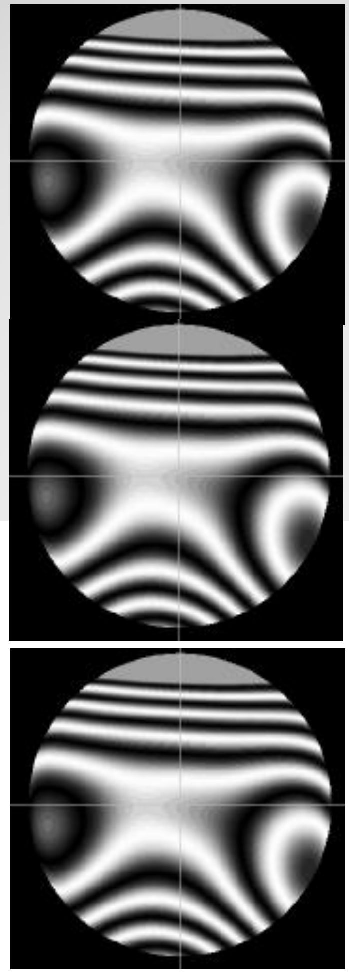
Including System Aberrations

Side View

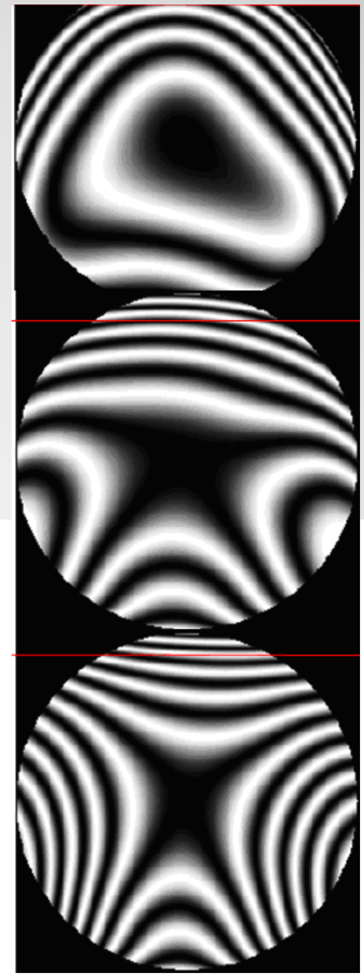


Beam : ~27mm

Simulated

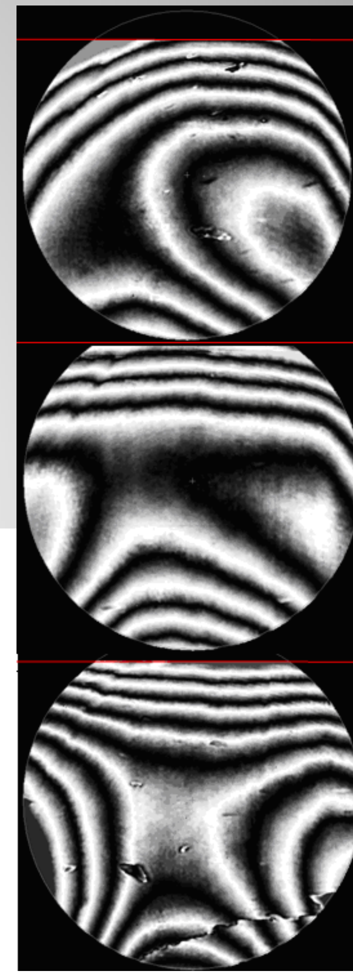


cat's eye position



coaxial position

Measured



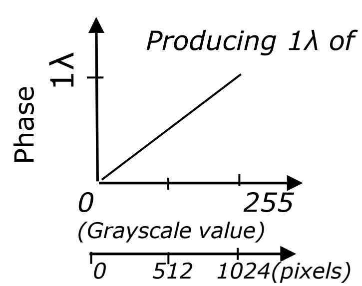
coaxial position

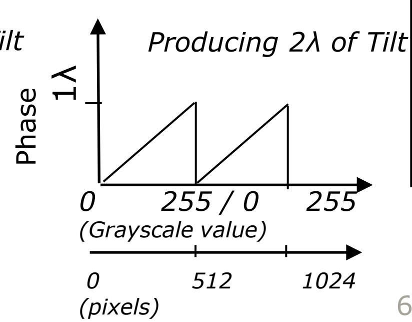
Jtrolinger@metrolaserinc.com

Key Components: SLM, Pixelcam*

SLM for a compensator

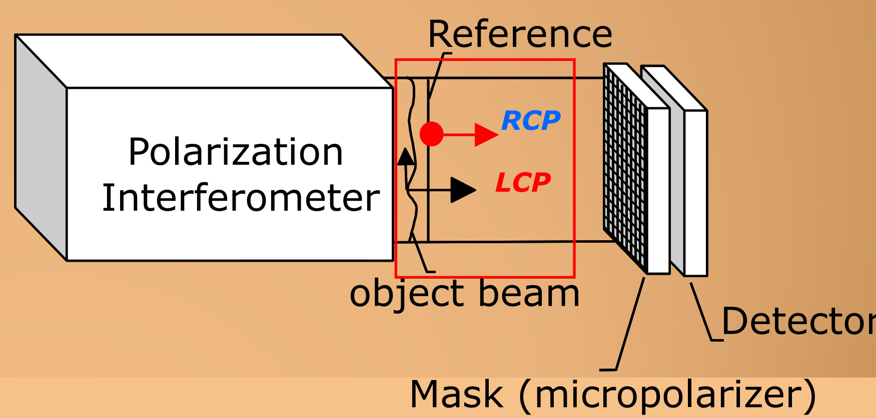
- Programmable holographic optical element
- Produce wavefronts of any shape and can simulate freeform optical surfaces
- Holoeye SLM
  - SLM can produce a phase up to 2п at 632.8nm
  - Assign 0 to 255 grayscale values to 0 to 2п (or 1λ)
  - Can generate higher phases by wrapping phase
  - Can provide more than 150 wave tilt
  - Pixel size ~ 19 microns.
  - 19.5 x 14.6mm size (1024 x768 pixels)

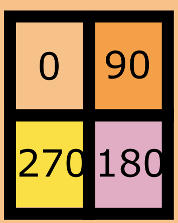




Pixelated Phasecam for a detector

- Spatial phase shifting interferometer
- Single shot, insensitive to vibration





Phase information of the object, *ΔΦ(x,y)* can be obtained from the 4 intensities on each unit cell.

$$I(x,y)=\frac{1}{2}\left(I_r+I_s+2\sqrt{I_r I_s}\cos\left(\Delta\phi(x,y)+2\alpha_p\right)\right)$$

Produced and Trademark by 4D Technologies, Inc, Tucson, AZ* ***http://www.4dtechnology.com*

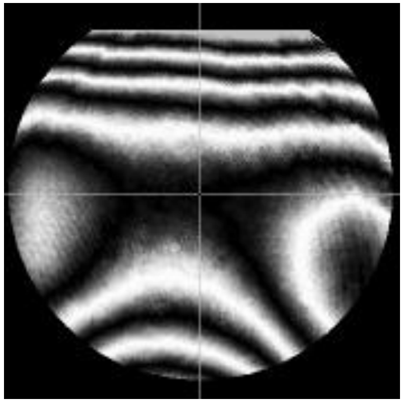
Small
Business
Innovation
Research

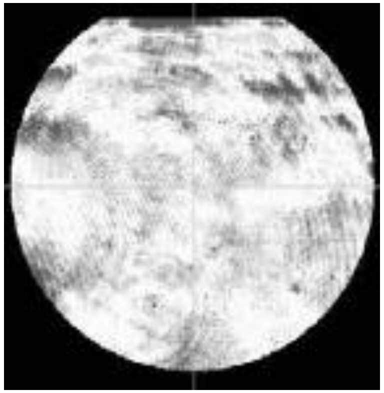
Enhanced Interferometry with a Programmable Spatial Light Modulator

MetroLaser Incorporated
Irvine, CA

INNOVATION

A unique optical inspection system incorporates a dynamic holographic optical element that combines and extends both Hartmann and digital interferometry with preconditioned wavefronts. The resulting system exhibits a wide dynamic range and will be especially useful for inspecting aspherical and free form optics





Before Correction *After Correction*
Wavefront Preconditioning

ACCOMPLISHMENTS

❖Demonstrated wide dynamic range optical inspection system
•Wavefront preconditioning via spatial light modulator.
•Hartmann & Interferometry in the same instrument
•Scanning Hartmann
•Extended dynamic range >150λ.
•Null point testing.

❖Hartmann provides information for programming SLM/HOE
❖Procedure to subtract system aberrations.

❖Accuracy of λ/20 with SLM in system.

COMMERCIALIZATION

- Basic concept patent application has been submitted
- Marketing to manufacturers of free form and aspherical optics
- Currently beta testing systems in service tests
- A wide range of customers have indicated interest
- Alliances made with two specific manufacturers
- This technology can provide significant savings of time and money over competitors
- This technology can enable inspections not provided by any competitors

APPLICATIONS/FUTURE WORK

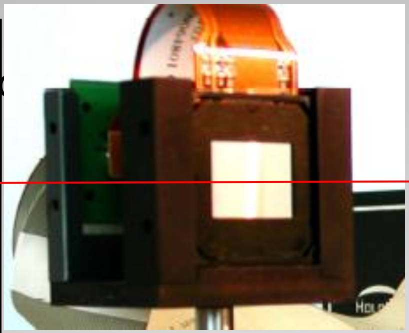
- Government and Commercial Applications
  - X-ray telescope mirrors and mandrels
  - Free form Optics
  - Aspherical Optics
  - SiC telescope Mirrors
  - Ogive windows
- Future Work
  - Additional Software for System Operation and Automation
  - System Packaging
  - Noise floor and resolution improvement

SBIR Phase II contract no. NNX08CA25C Date: May, 2010 **NON-PROPRIETARY DATA for Public Release**

Contacts:MetroLaser, Inc. 9495530688
jtrolinger@metrolaserinc.com

SLM Calibration

SLM

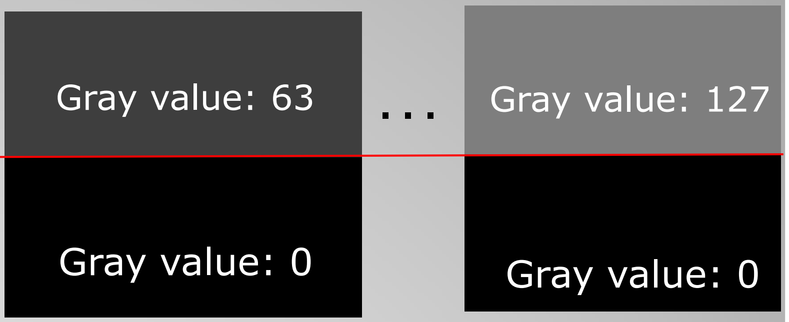


Applied gray values on the SLM

Applied gray values on the SLM

Gray scale value is varied on upper half of SLM

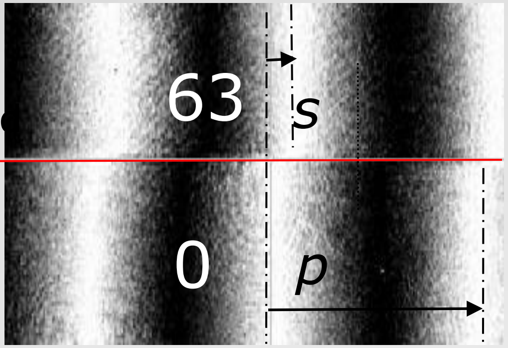
Gray scale value is held constant at 0 on lower half of SLM

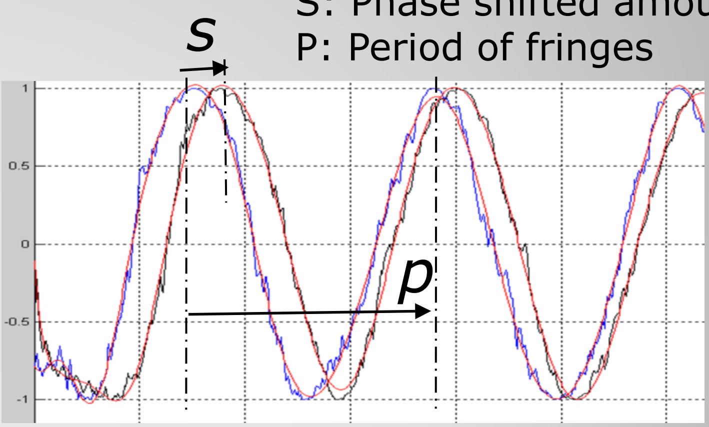


Interferogram Result

S: Phase shifted amount
P: Period of fringes

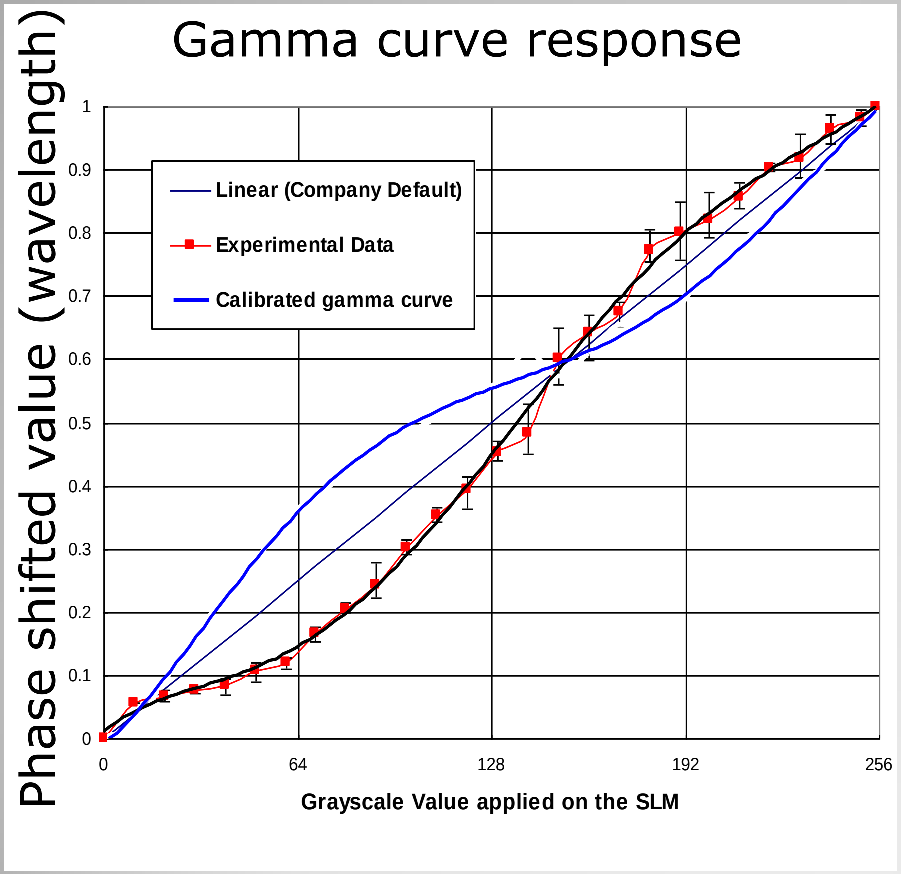
Phase shift vs. gray scale value is measured interferometrically





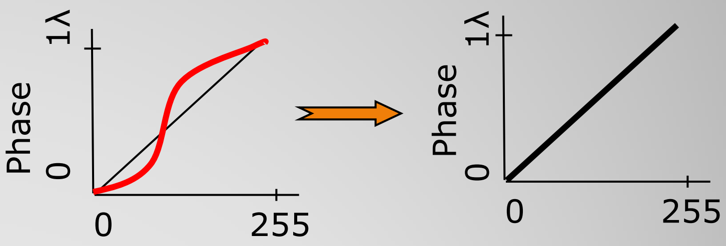
- Relative phase shift recorded to achieve an accuracy of data
- Gray value was varied from 0 to 255 on the top half, while it was held constant (0) on the bottom half
- Phase shifted vs applied gray value on the SLM produces gamma curve

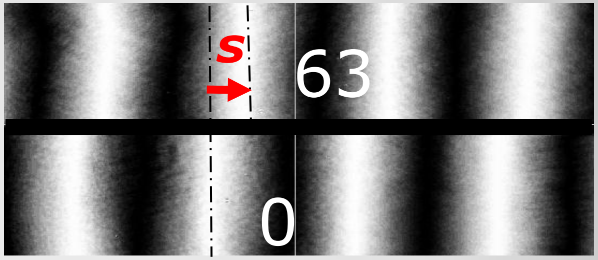
Corrected Gamma Curve



The calibrated gamma curve (blue color), is used to linearize the phase vs. gray scale response (red curve)

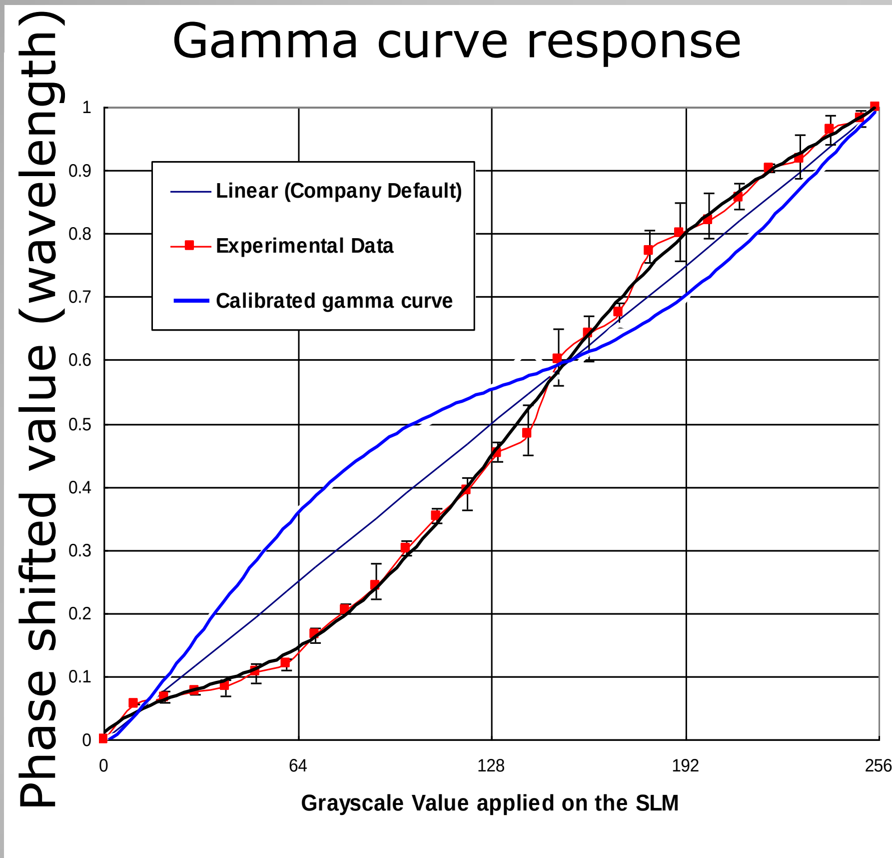
Errors when producing 1λ of tilt and corrected one after calibration





S = 0.25λ shift when 63 value applied

Corrected Gamma Curve



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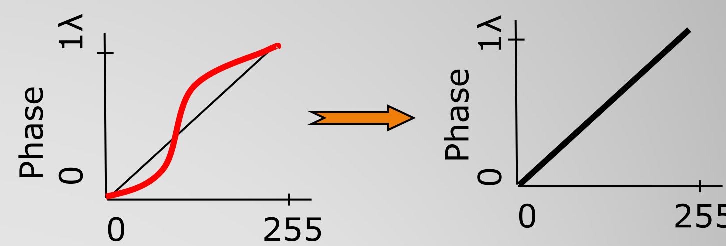
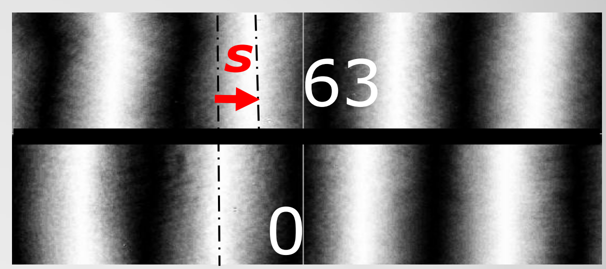
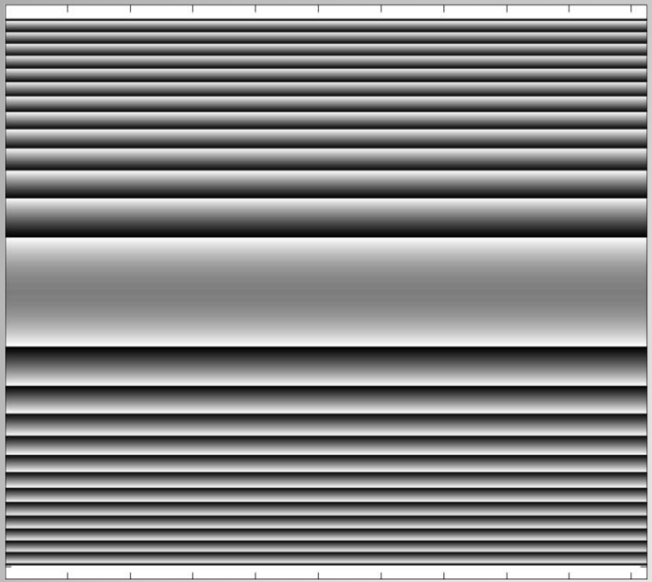




S = 0.25λ shift when 63 value applied

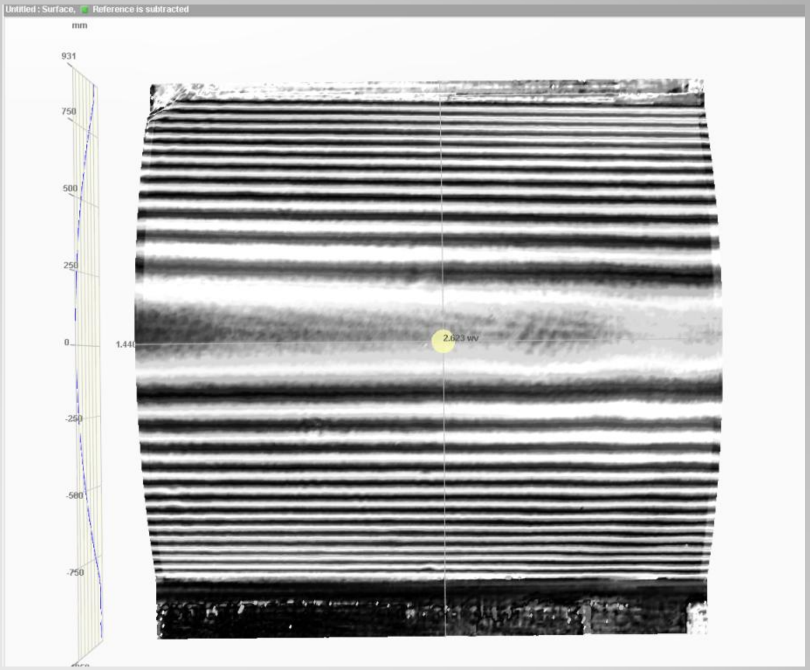
Producing cylindrical wavefronts

Applied Phase on the SLM



$\Phi \sim a\, y^2$
Matlab formula used to generate the phase.

Interferogram on the pixelcam

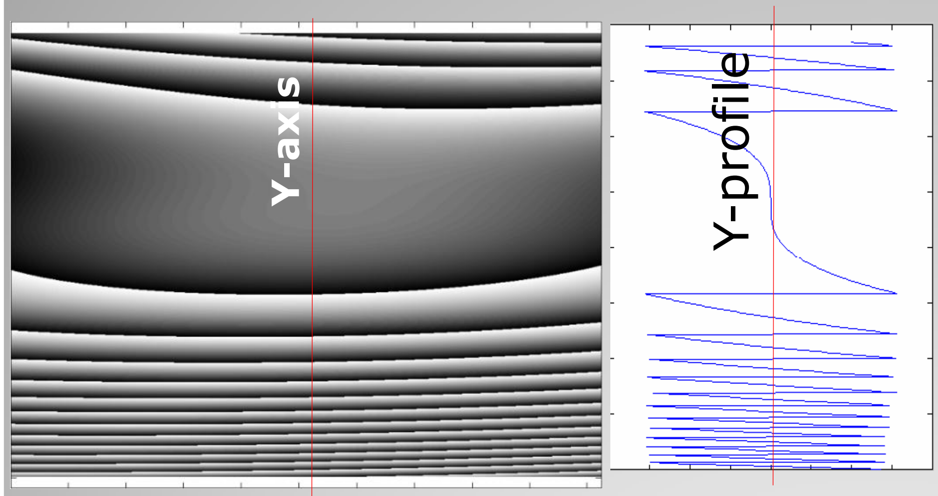


- Cylindrical wrapped phase written by Matlab code and applied on the SLM, which is good candidate compensating phase for a Mandrel.

- Phase produced and shown by the interferogram on the pixelcam

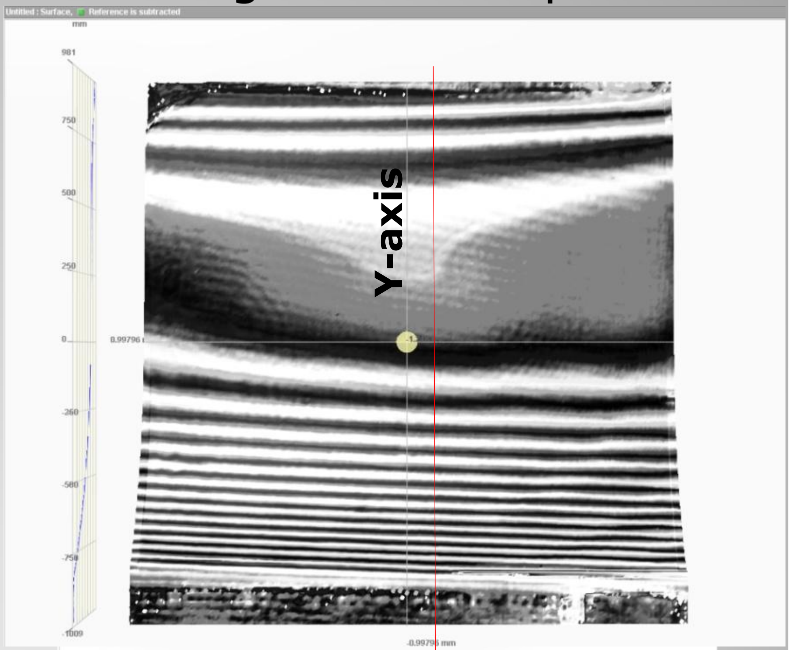
Producing arbitrary wavefronts

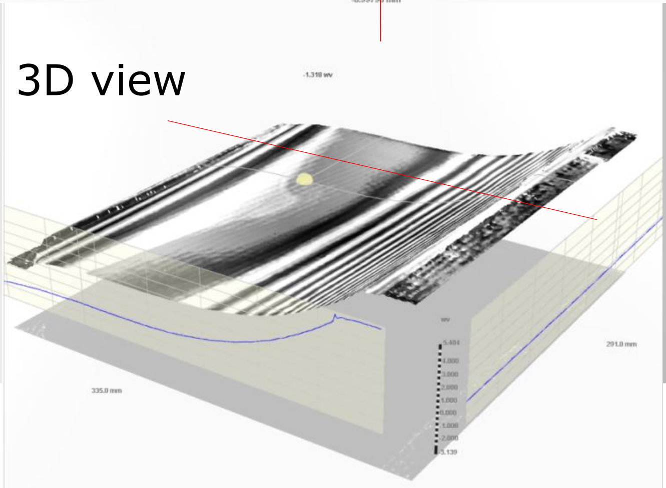
Applied Phase on the SLM



Φ = 20.(y-0.25)^3 – x.^{2} + x.*y + x.*y^3*
Matlab formula used to generate the phase

Interferogram on the pixelcam

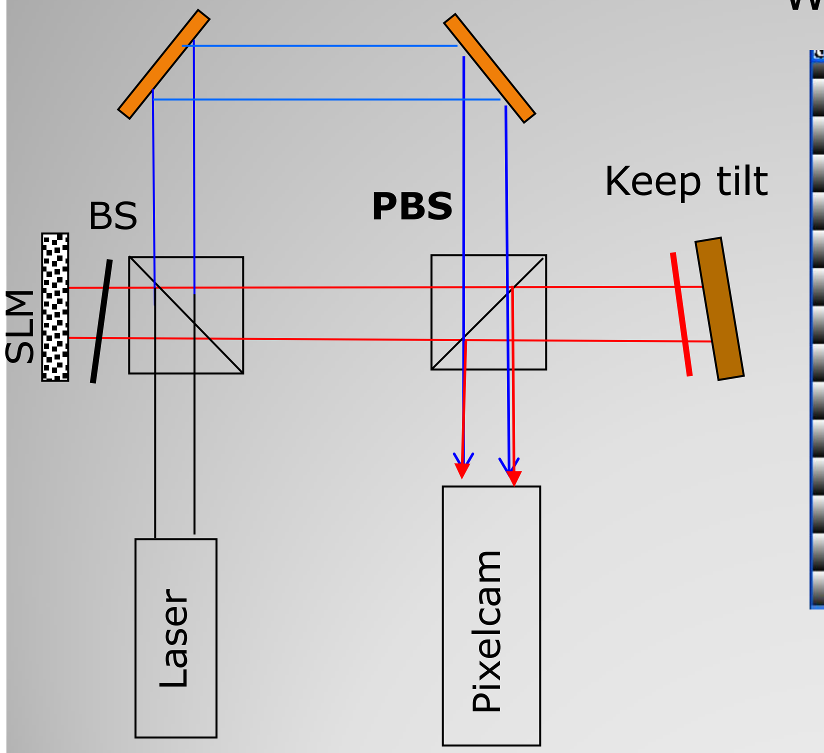




- Arbitrary wrapped phase written by Matlab code and applied on the SLM
- Phase produced and shown by the interferogram on the pixelcam

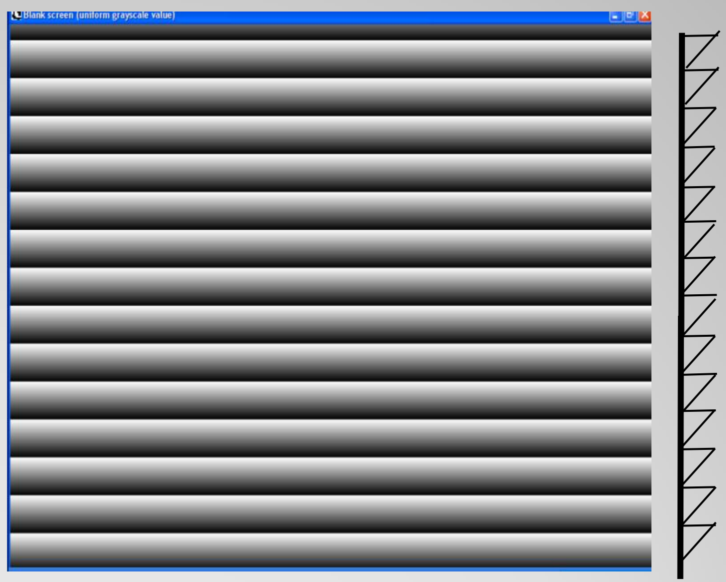
Compensation of Tilt

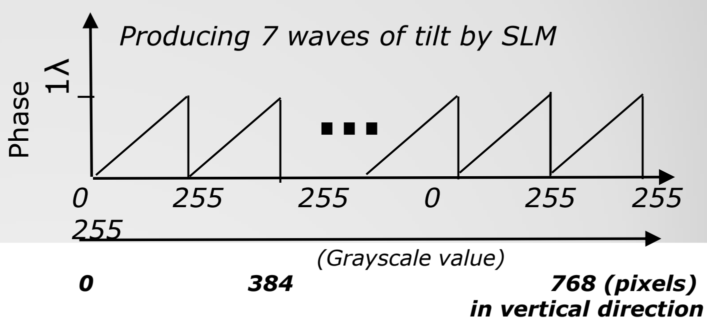
-Applied compensating tilt by the SLM



(Various waveplates and telescopes not shown)

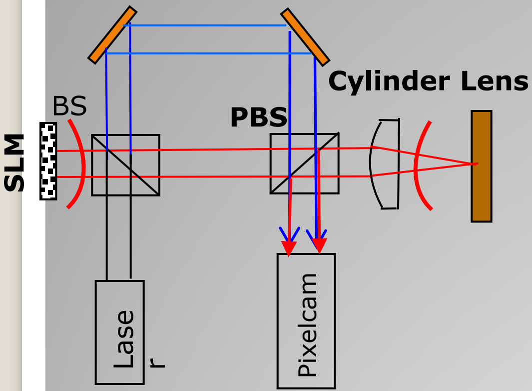
Wrapped phase applied on the SLM



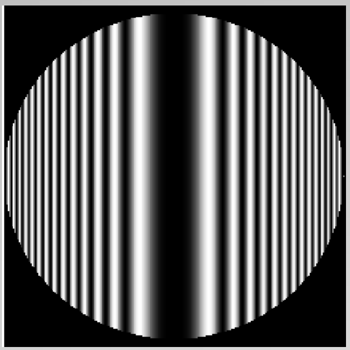


Compensating wrapped phase applied on the SLM

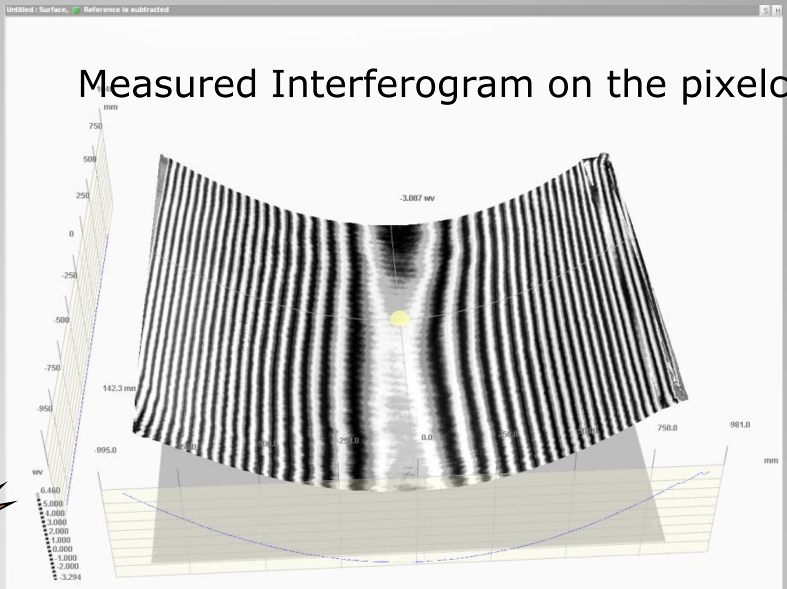
Compensation of Cylindrical wavefronts



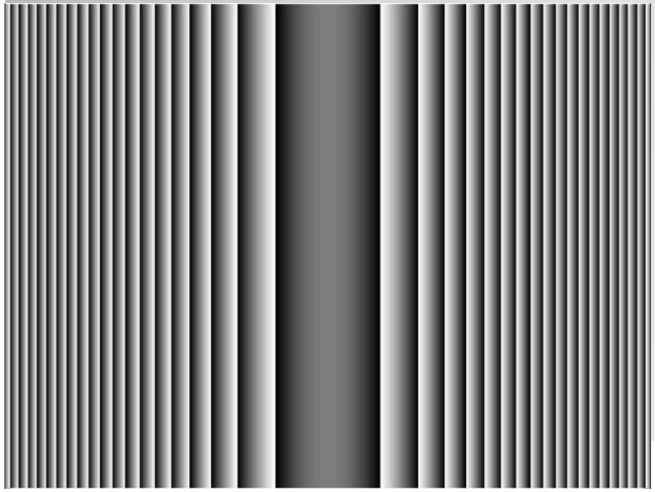
Simulation



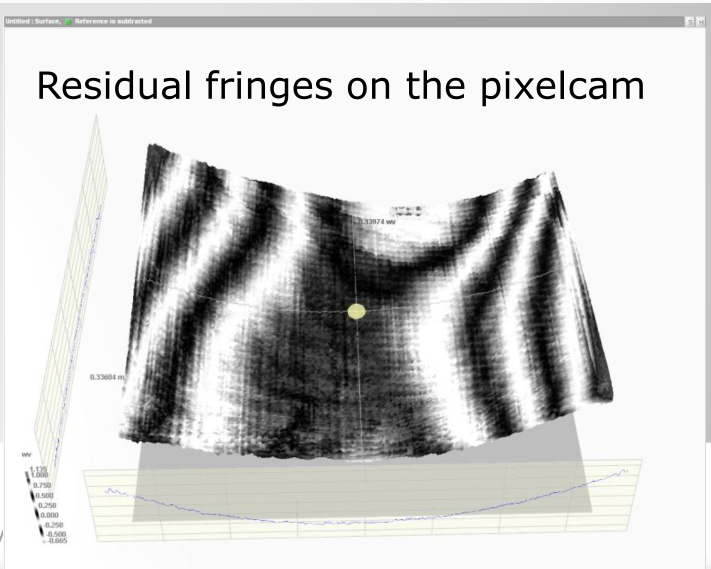
Measured Interferogram on the pixelcam



Applied Phase on the SLM

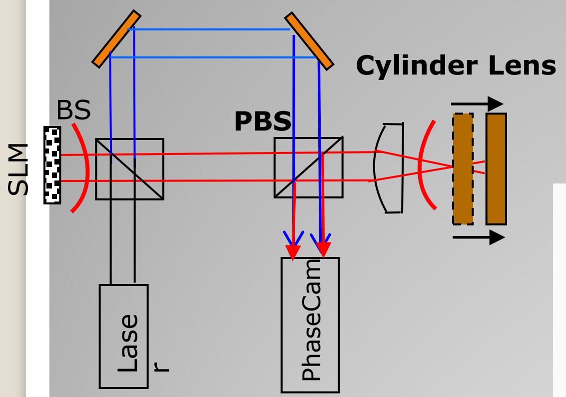


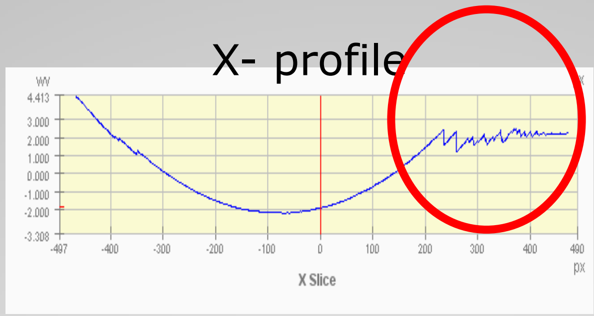
Residual fringes on the pixelcam



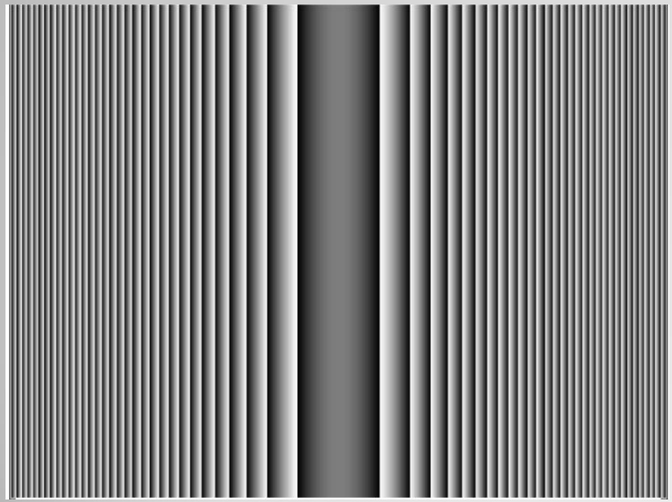
Compensation of Cylindrical wavefronts

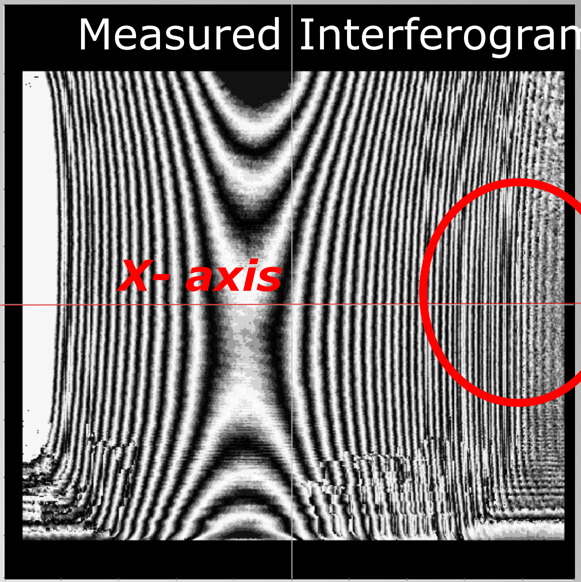
Extreme Case

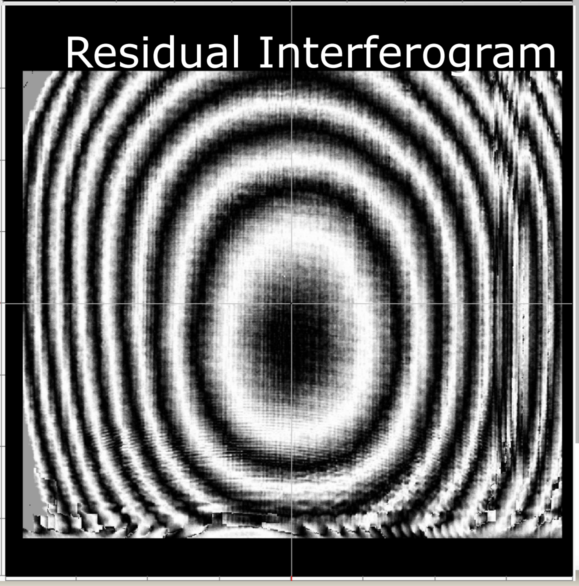




Applied Phase on the SLM

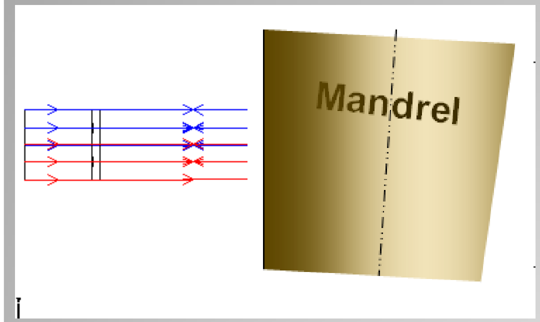


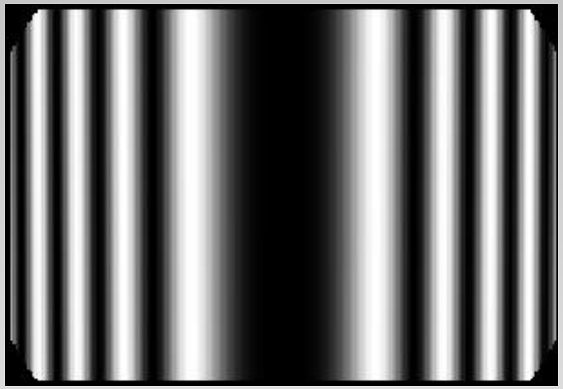


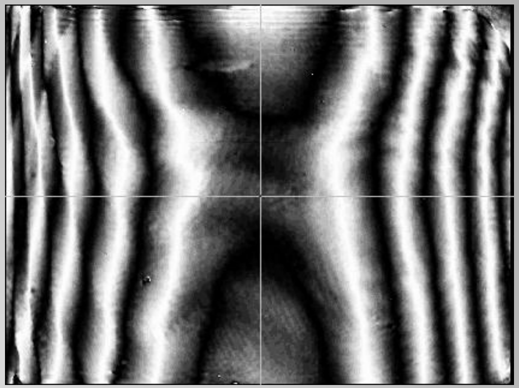


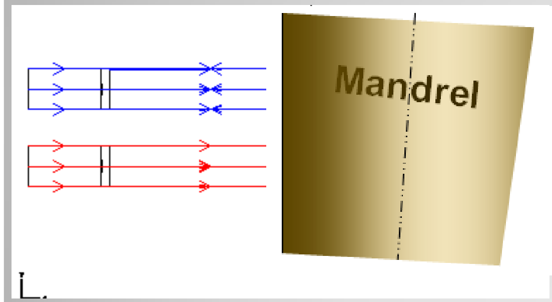
The phase on SLM is used to bring the dense fringes down into the measurement range of the pixelcam. i.e: extended dynamic range.

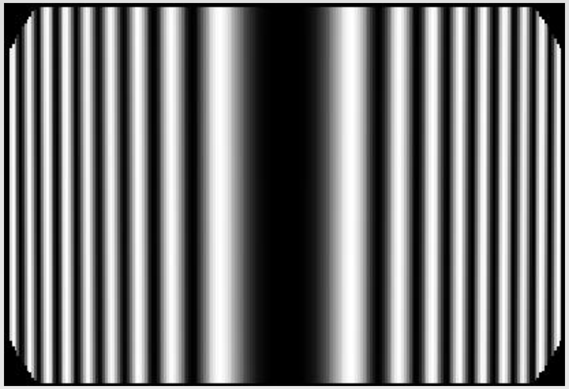
Wavefront Differences at Different Heights of Mandre

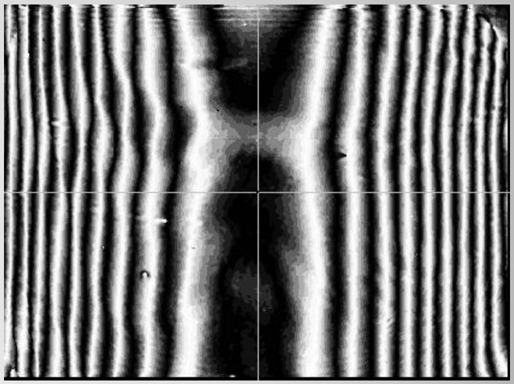












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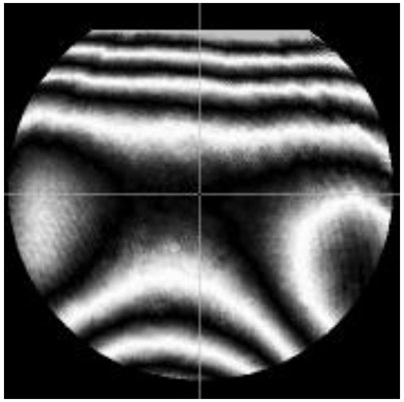

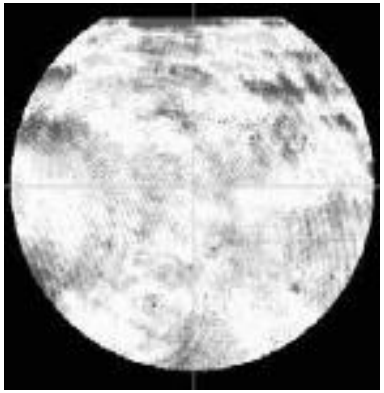

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